US010431719B2

(12) **United States Patent**
Cok et al.

(10) **Patent No.: US 10,431,719 B2**
(45) **Date of Patent: Oct. 1, 2019**

(54) **DISPLAY WITH COLOR CONVERSION**

(71) Applicant: **X-Celeprint Limited**, Cork (IE)

(72) Inventors: **Ronald S. Cok**, Rochester, NY (US); **Christopher Bower**, Raleigh, NC (US); **Matthew Meitl**, Durham, NC (US)

(73) Assignee: **X-Celeprint Limited**, Cork (IE)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 757 days.

(21) Appl. No.: **14/930,363**

(22) Filed: **Nov. 2, 2015**

(65) **Prior Publication Data**

US 2017/0122502 A1 May 4, 2017

(51) **Int. Cl.**

H01L 21/00	(2006.01)
H01L 33/38	(2010.01)

(Continued)

(52) **U.S. Cl.**

CPC ***H01L 33/385*** (2013.01); ***F21K 9/60*** (2016.08); ***F21V 9/08*** (2013.01); ***G02B 26/04*** (2013.01);

(Continued)

(58) **Field of Classification Search**

CPC H01L 33/385; H01L 23/4821; H01L 23/5381; H01L 25/0753; H01L 25/167; H01L 27/156; H01L 33/36; H01L 33/38; H01L 33/48; H01L 33/50; H01L 33/502; H01L 33/508; H01L 25/27; H01L 25/156; H01L 33/20; H01L 33/405; H01L 33/58; H05K 1/0306; H05K 1/09; H05K 1/181; H05K 1/182

See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,746,202	A	5/1988	Perilloux et al.
5,060,027	A	10/1991	Hart et al.

(Continued)

FOREIGN PATENT DOCUMENTS

CN	103677427	A	3/2014
EP	1662301	A1	5/2006

(Continued)

OTHER PUBLICATIONS

Matioli, E. et al., High-brightness polarized light-emitting diodes, Light: Science & Applications, 1:e22:1-7 (2012).

(Continued)

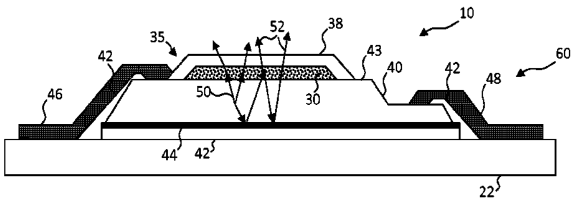
Primary Examiner — Richard A Booth

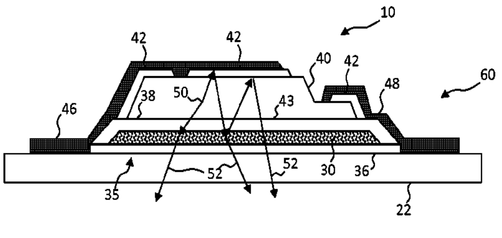
(74) *Attorney, Agent, or Firm* — William R. Haulbrook; Michael D. Schmitt; Choate, Hall & Stewart LLP

(57) **ABSTRACT**

A color-conversion structure includes an article comprising a color-conversion material disposed within a color-conversion layer. At least a portion of a tether is within or extends from the article. The color-conversion structure can be disposed over a sacrificial portion of a substrate to form a micro-transfer printable device and micro-transfer printed to a display substrate. The color-conversion structure can include an light-emitting diode or laser diode that is over or under the article. Alternatively, the article is located on a side of a display substrate opposite an inorganic light-emitting diode. A display includes an array of color-conversion structures disposed on a display substrate.

21 Claims, 13 Drawing Sheets





(51) **Int. Cl.**

G09G 3/32	(2016.01)
H01L 23/482	(2006.01)
H01L 23/538	(2006.01)
H01L 25/075	(2006.01)
H01L 33/62	(2010.01)
H01L 33/50	(2010.01)
H01L 33/60	(2010.01)
H05B 33/08	(2006.01)
G02B 26/04	(2006.01)
G02F 1/167	(2019.01)
H01L 25/16	(2006.01)
H01L 33/36	(2010.01)
H01L 33/48	(2010.01)
H05K 1/03	(2006.01)
H05K 1/09	(2006.01)
H05K 1/18	(2006.01)
H05K 5/00	(2006.01)
G09G 3/22	(2006.01)
H01L 27/15	(2006.01)
F21V 9/08	(2018.01)
H01L 33/58	(2010.01)
F21K 9/60	(2016.01)
H01L 33/20	(2010.01)
H01L 33/40	(2010.01)
F21Y 105/10	(2016.01)
F21Y 115/10	(2016.01)
F21Y 113/13	(2016.01)
F21Y 101/00	(2016.01)
F21Y 105/00	(2016.01)

(52) **U.S. Cl.**

CPC ***G02F 1/167*** (2013.01); ***G09G 3/22*** (2013.01); ***G09G 3/32*** (2013.01); ***H01L 23/4821*** (2013.01); ***H01L 23/5381*** (2013.01); ***H01L 25/0753*** (2013.01); ***H01L 25/167*** (2013.01); ***H01L 27/156*** (2013.01); ***H01L 33/36*** (2013.01); ***H01L 33/38*** (2013.01); ***H01L 33/48*** (2013.01); ***H01L 33/50*** (2013.01); ***H01L 33/502*** (2013.01); ***H01L 33/508*** (2013.01); ***H01L 33/58*** (2013.01); ***H01L 33/60*** (2013.01); ***H01L 33/62*** (2013.01); ***H05B 33/089*** (2013.01); ***H05K 1/0306*** (2013.01); ***H05K 1/09*** (2013.01); ***H05K 1/181*** (2013.01); ***H05K 1/182*** (2013.01); ***H05K 5/0017*** (2013.01); *F21Y 2101/00* (2013.01); *F21Y 2105/00* (2013.01); *F21Y 2105/10* (2016.08); *F21Y 2113/13* (2016.08); *F21Y 2115/10* (2016.08); *G09G 2300/0452* (2013.01); *G09G 2300/0842* (2013.01); *G09G 2310/0264* (2013.01); *H01L 33/20* (2013.01); *H01L 33/405* (2013.01); *H01L 2224/18* (2013.01); *H01L 2224/73267* (2013.01); *H01L 2224/92244* (2013.01); *H05K 2201/0329* (2013.01); *H05K 2201/10106* (2013.01); *H05K 2201/10128* (2013.01); *H05K 2201/10166* (2013.01)

(56) References Cited

U.S. PATENT DOCUMENTS

5,550,066	A	8/1996	Tang et al.	
5,621,555	A	4/1997	Park	
5,625,202	A	4/1997	Chai	
5,748,161	A	5/1998	Lebby et al.	
5,815,303	A	9/1998	Berlin	
5,994,722	A	11/1999	Averbeck et al.	
6,025,730	A	2/2000	Akram et al.	
6,084,579	A	7/2000	Hirano	
6,087,680	A	7/2000	Gramann et al.	
6,142,358	A	11/2000	Cohn et al.	
6,143,672	A	11/2000	Ngo et al.	
6,169,294	B1	1/2001	Biing-Jye et al.	
6,184,477	B1	2/2001	Tanahashi	
6,278,242	B1	8/2001	Cok et al.	
6,288,824	B1	9/2001	Kastalsky	
6,340,999	B1	1/2002	Masuda et al.	
6,392,340	B2	5/2002	Yoneda et al.	
6,403,985	B1	6/2002	Fan et al.	
6,410,942	B1	6/2002	Thibeault et al.	
6,466,281	B1	10/2002	Huang et al.	
6,504,180	B1	1/2003	Heremans et al.	
6,577,367	B2	6/2003	Kim	
6,650,382	B1	11/2003	Sumida et al.	
6,660,457	B1	12/2003	Imai et al.	
6,703,780	B2	3/2004	Shiang et al.	
6,717,560	B2	4/2004	Cok et al.	
6,756,576	B1	6/2004	McElroy et al.	
6,812,637	B2	11/2004	Cok et al.	
6,828,724	B2	12/2004	Burroughes	
6,933,532	B2	8/2005	Arnold et al.	
6,969,624	B2	11/2005	Iwafuchi et al.	
6,975,369	B1	12/2005	Burkholder	
7,009,220	B2	3/2006	Oohata	
7,012,382	B2	3/2006	Cheang et al.	
7,091,523	B2	8/2006	Cok et al.	
7,098,589	B2	8/2006	Erchak et al.	
7,127,810	B2	10/2006	Kasuga et al.	
7,129,457	B2	10/2006	McElroy et al.	
7,195,733	B2	3/2007	Rogers et al.	
7,259,391	B2	8/2007	Liu et al.	
7,288,753	B2	10/2007	Cok	
7,402,951	B2	7/2008	Cok	
7,417,648	B2	8/2008	Credelle	
7,420,221	B2	9/2008	Nagai	
7,466,075	B2	12/2008	Cok et al.	
7,521,292	B2	4/2009	Rogers et al.	
7,557,367	B2	7/2009	Rogers et al.	
7,586,497	B2	9/2009	Boroson et al.	
7,605,053	B2	10/2009	Couillard et al.	
7,614,757	B2	11/2009	Nesterenko et al.	
7,622,367	B1	11/2009	Nuzzo et al.	
7,629,955	B2	12/2009	Asao et al.	
7,662,545	B2	2/2010	Nuzzo et al.	
7,687,812	B2	3/2010	Louwsma et al.	
7,704,684	B2	4/2010	Rogers et al.	
7,791,271	B2	9/2010	Cok et al.	
7,799,699	B2	9/2010	Nuzzo et al.	
7,816,856	B2	10/2010	Cok et al.	
7,834,541	B2 *	11/2010	Cok	B82Y 20/00 313/110
7,872,722	B2	1/2011	Kimura	
7,893,612	B2	2/2011	Cok	
7,898,734	B2	3/2011	Coleman et al.	
7,919,342	B2	4/2011	Cok	
7,927,976	B2	4/2011	Menard	
7,932,123	B2	4/2011	Rogers et al.	
7,943,491	B2	5/2011	Nuzzo et al.	
7,948,172	B2	5/2011	Cok et al.	
7,969,085	B2	6/2011	Cok	
7,972,875	B2	7/2011	Rogers et al.	
7,982,296	B2	7/2011	Nuzzo et al.	
7,990,058	B2	8/2011	Cok et al.	
7,999,454	B2	8/2011	Winters et al.	
8,004,758	B2	8/2011	Coleman et al.	
8,029,139	B2	10/2011	Ellinger et al.	
8,039,847	B2	10/2011	Nuzzo et al.	
8,058,663	B2	11/2011	Fan et al.	
8,198,621	B2	6/2012	Rogers et al.	
8,207,547	B2	6/2012	Lin	
8,243,027	B2	8/2012	Hotelling et al.	
8,261,660	B2	9/2012	Menard	
8,288,843	B2	10/2012	Kojima et al.	
8,334,545	B2	12/2012	Levermore et al.	
8,394,706	B2	3/2013	Nuzzo et al.	
8,440,546	B2	5/2013	Nuzzo et al.	

(56) References Cited

U.S. PATENT DOCUMENTS

8,450,927	B2	5/2013	Lenk et al.
8,470,701	B2	6/2013	Rogers et al.
8,502,192	B2	8/2013	Kwak et al.
8,506,867	B2	8/2013	Menard
8,536,584	B2	9/2013	Yao
8,581,827	B2	11/2013	Park et al.
8,596,846	B2	12/2013	Yankov et al.
8,599,118	B2	12/2013	Cok
8,619,011	B2	12/2013	Kimura
8,664,699	B2	3/2014	Nuzzo et al.
8,686,447	B2	4/2014	Tomoda et al.
8,722,458	B2	5/2014	Rogers et al.
8,735,932	B2	5/2014	Kim et al.
8,754,396	B2	6/2014	Rogers et al.
8,766,970	B2	7/2014	Chien et al.
8,791,474	B1	7/2014	Bibl et al.
8,794,501	B2	8/2014	Bibl et al.
8,803,857	B2	8/2014	Cok
8,817,369	B2	8/2014	Daiku
8,829,663	B2	9/2014	Pohl et al.
8,836,624	B2	9/2014	Roberts et al.
8,854,294	B2	10/2014	Sakariya
8,860,051	B2	10/2014	Fellows et al.
8,877,648	B2	11/2014	Bower et al.
8,884,844	B2	11/2014	Yang et al.
8,889,485	B2	11/2014	Bower
8,895,406	B2	11/2014	Rogers et al.
8,896,505	B2	11/2014	Cok et al.
8,901,578	B2	12/2014	Kobayakawa et al.
8,902,152	B2	12/2014	Bai et al.
8,912,020	B2	12/2014	Bedell et al.
8,946,760	B2	2/2015	Kim
8,987,765	B2	3/2015	Bibl et al.
9,022,632	B2	5/2015	Kim et al.
9,048,449	B2	6/2015	Kim et al.
9,105,813	B1	8/2015	Chang
9,153,171	B2	10/2015	Sakariya et al.
9,178,123	B2	11/2015	Sakariya et al.
9,202,996	B2	12/2015	Orsley et al.
9,226,361	B2	12/2015	Toth
9,277,618	B2	3/2016	Odnoblyudov et al.
9,293,422	B1	3/2016	Parsa et al.
9,308,649	B2	4/2016	Golda et al.
9,329,430	B2	5/2016	Erinjippurath et al.
9,343,042	B2	5/2016	Miller et al.
9,368,683	B1	6/2016	Meitl et al.
9,412,977	B2	8/2016	Rohatgi
9,437,782	B2	9/2016	Bower et al.
9,444,015	B2	9/2016	Bower et al.
9,520,537	B2	12/2016	Bower et al.
9,537,069	B1	1/2017	Bower et al.
9,626,908	B2	4/2017	Sakariya et al.
9,698,308	B2	7/2017	Bower et al.
9,705,042	B2	7/2017	Bower et al.
9,716,082	B2	7/2017	Bower et al.
9,741,785	B2	8/2017	Bower et al.
9,860,955	B2	1/2018	Kim et al.
9,871,345	B2	1/2018	Bower et al.
2001/0022564	A1	9/2001	Youngquist et al.
2002/0096994	A1	7/2002	Iwafuchi et al.
2002/0171792	A1*	11/2002	Kubota G02F 1/133555 349/114
2004/0080483	A1	4/2004	Chosa
2004/0180476	A1	9/2004	Kazlas et al.
2004/0212296	A1	10/2004	Nakamura et al.
2004/0227704	A1	11/2004	Wang et al.
2004/0252933	A1	12/2004	Sylvester et al.
2005/0006657	A1	1/2005	Terashita
2005/0012076	A1	1/2005	Morioka
2005/0116621	A1*	6/2005	Bellmann B41M 5/265 313/503
2005/0140275	A1	6/2005	Park
2005/0168987	A1	8/2005	Tamaoki et al.
2005/0202595	A1	9/2005	Yonehara et al.
2005/0264472	A1	12/2005	Rast
2005/0275615	A1	12/2005	Kahen et al.
2005/0285246	A1	12/2005	Haba et al.
2006/0051900	A1	3/2006	Shizuno
2006/0063309	A1	3/2006	Sugiyama et al.
2006/0273862	A1	12/2006	Shimmura
2006/0289972	A1	12/2006	Nishimura et al.
2007/0035340	A1	2/2007	Kimura
2007/0077349	A1	4/2007	Newman et al.
2007/0182809	A1	8/2007	Yarid et al.
2007/0201056	A1	8/2007	Cok et al.
2008/0108171	A1	5/2008	Rogers et al.
2008/0211734	A1	9/2008	Huitema et al.
2008/0296717	A1	12/2008	Beroz et al.
2009/0045420	A1	2/2009	Eng et al.
2009/0146921	A1	6/2009	Takahashi
2009/0278142	A1	11/2009	Watanabe et al.
2009/0295706	A1	12/2009	Feng
2009/0315054	A1	12/2009	Kim et al.
2010/0038655	A1	2/2010	Chen et al.
2010/0060553	A1	3/2010	Zimmerman et al.
2010/0078670	A1	4/2010	Kim et al.
2010/0123134	A1	5/2010	Nagata
2010/0123268	A1	5/2010	Menard
2010/0148198	A1	6/2010	Sugizaki et al.
2010/0149117	A1	6/2010	Chien et al.
2010/0186883	A1	7/2010	Tomoda
2010/0190293	A1	7/2010	Maeda et al.
2010/0201253	A1	8/2010	Cok et al.
2010/0207852	A1	8/2010	Cok
2010/0214245	A1	8/2010	Hirota
2010/0214247	A1	8/2010	Tang et al.
2010/0248484	A1	9/2010	Bower et al.
2010/0258710	A1	10/2010	Wiese et al.
2010/0270912	A1	10/2010	Ko
2010/0289115	A1	11/2010	Akiyama et al.
2010/0317132	A1	12/2010	Rogers et al.
2010/0321414	A1	12/2010	Muroi et al.
2010/0328268	A1	12/2010	Teranishi et al.
2011/0032277	A1	2/2011	Lee et al.
2011/0043435	A1	2/2011	Hebenstreit et al.
2011/0069013	A1	3/2011	Rabenstein et al.
2011/0108800	A1	5/2011	Pan
2011/0120678	A1	5/2011	Palm
2011/0205448	A1	8/2011	Takata
2011/0211348	A1	9/2011	Kim
2011/0242027	A1	10/2011	Chang
2012/0056835	A1	3/2012	Choo et al.
2012/0062135	A1	3/2012	Tamaki et al.
2012/0105518	A1	5/2012	Kang et al.
2012/0119249	A1	5/2012	Kim et al.
2012/0126229	A1	5/2012	Bower
2012/0141799	A1	6/2012	Kub et al.
2012/0206428	A1	8/2012	Cok
2012/0206499	A1	8/2012	Cok
2012/0223636	A1	9/2012	Shin et al.
2012/0223875	A1	9/2012	Lau et al.
2012/0228669	A1	9/2012	Bower et al.
2012/0236022	A1	9/2012	Homma et al.
2012/0256163	A1	10/2012	Yoon et al.
2012/0274669	A1	11/2012	Neal
2012/0281028	A1	11/2012	Orlick et al.
2012/0314388	A1	12/2012	Bower et al.
2012/0320566	A1	12/2012	Namekata
2013/0006524	A1	1/2013	Sasaki et al.
2013/0010405	A1	1/2013	Rothkopf et al.
2013/0015483	A1	1/2013	Shimokawa et al.
2013/0016494	A1	1/2013	Speier et al.
2013/0036928	A1	2/2013	Rogers et al.
2013/0069275	A1	3/2013	Menard et al.
2013/0088416	A1	4/2013	Smith et al.
2013/0128585	A1	5/2013	Bibl et al.
2013/0196474	A1	8/2013	Meitl et al.
2013/0207964	A1	8/2013	Fleck et al.
2013/0221355	A1	8/2013	Bower et al.
2013/0248889	A1	9/2013	Lin
2013/0257264	A1	10/2013	Tamaki et al.
2013/0273695	A1	10/2013	Menard et al.
2013/0278513	A1	10/2013	Jang
2014/0014960	A1	1/2014	Yamazaki et al.

(56) References Cited

U.S. PATENT DOCUMENTS

2014/0027709	A1	1/2014	Higginson et al.	
2014/0082934	A1	3/2014	Cok	
2014/0084240	A1	3/2014	Hu et al.	
2014/0084482	A1	3/2014	Hu et al.	
2014/0085214	A1	3/2014	Cok	
2014/0104157	A1	4/2014	Burns et al.	
2014/0104243	A1	4/2014	Sakariya et al.	
2014/0111442	A1	4/2014	Cok et al.	
2014/0146273	A1	5/2014	Kim et al.	
2014/0159043	A1	6/2014	Sakariya et al.	
2014/0159065	A1	6/2014	Hu et al.	
2014/0175498	A1	6/2014	Lai	
2014/0183446	A1	7/2014	Nago et al.	
2014/0192079	A1	7/2014	Lee et al.	
2014/0197509	A1	7/2014	Haddad et al.	
2014/0198373	A1	7/2014	Ray	
2014/0217448	A1	8/2014	Kim et al.	
2014/0231839	A1	8/2014	Jeon et al.	
2014/0231851	A1	8/2014	Tsai et al.	
2014/0240617	A1	8/2014	Fukutome et al.	
2014/0264763	A1	9/2014	Meitl et al.	
2014/0267683	A1	9/2014	Bibl et al.	
2014/0306248	A1	10/2014	Ahn et al.	
2014/0319486	A1	10/2014	Hong	
2014/0339495	A1	11/2014	Bibl et al.	
2014/0340900	A1*	11/2014	Bathurst	F21K 9/00 362/249.02
2014/0367633	A1	12/2014	Bibl et al.	
2014/0367705	A1	12/2014	Bibl et al.	
2015/0003040	A1	1/2015	Bessho et al.	
2015/0021632	A1	1/2015	Taghizadeh et al.	
2015/0135525	A1	5/2015	Bower	
2015/0137153	A1	5/2015	Bibl et al.	
2015/0169011	A1	6/2015	Bibl et al.	
2015/0179453	A1	6/2015	Cheng et al.	
2015/0263066	A1	9/2015	Hu et al.	
2015/0280066	A1	10/2015	Fujimura et al.	
2015/0280089	A1	10/2015	Obata et al.	
2015/0296580	A1	10/2015	Kim et al.	
2015/0308634	A1	10/2015	van de Ven et al.	
2015/0318328	A1	11/2015	Bibl et al.	
2015/0327388	A1	11/2015	Menard et al.	
2015/0362165	A1	12/2015	Chu et al.	
2015/0370130	A1	12/2015	Lin	
2015/0371585	A1	12/2015	Bower et al.	
2015/0371974	A1	12/2015	Bower et al.	
2015/0372051	A1	12/2015	Bower et al.	
2015/0372052	A1	12/2015	Bower et al.	
2015/0372053	A1	12/2015	Bower et al.	
2015/0372187	A1	12/2015	Bower et al.	
2015/0373793	A1	12/2015	Bower et al.	
2016/0004123	A1	1/2016	Tanabe	
2016/0005721	A1	1/2016	Bower et al.	
2016/0018094	A1	1/2016	Bower et al.	
2016/0056725	A1	2/2016	Kim et al.	
2016/0057822	A1	2/2016	Chu	
2016/0057827	A1	2/2016	Miskin	
2016/0057832	A1	2/2016	Briggs et al.	
2016/0064363	A1	3/2016	Bower et al.	
2016/0085120	A1	3/2016	Xu	
2016/0093600	A1	3/2016	Bower et al.	
2016/0131329	A1	5/2016	Park et al.	
2016/0260388	A1	9/2016	Yata et al.	
2016/0266697	A1	9/2016	Cheng et al.	
2016/0343772	A1	11/2016	Bower et al.	
2016/0351539	A1	12/2016	Bower et al.	
2016/0364030	A1	12/2016	Peana et al.	
2017/0005244	A1	1/2017	Bower et al.	
2017/0025075	A1	1/2017	Cok et al.	
2017/0025484	A1	1/2017	Forrest et al.	
2017/0047393	A1	2/2017	Bower et al.	
2017/0048976	A1	2/2017	Prevatte et al.	
2017/0061842	A1	3/2017	Cok et al.	
2017/0068362	A1	3/2017	Den Boer et al.	
2017/0092863	A1	3/2017	Bower et al.	
2017/0102797	A1	4/2017	Cok	
2017/0133818	A1	5/2017	Cok	
2017/0167703	A1	6/2017	Cok	
2017/0186740	A1	6/2017	Cok et al.	
2017/0187976	A1	6/2017	Cok	
2017/0206845	A1	7/2017	Sakariya et al.	
2017/0250219	A1	8/2017	Bower et al.	
2017/0256521	A1	9/2017	Cok et al.	
2017/0256522	A1	9/2017	Cok et al.	
2017/0287882	A1	10/2017	Cok et al.	
2017/0352646	A1	12/2017	Bower et al.	
2017/0357127	A1	12/2017	Cok et al.	
2017/0358717	A1	12/2017	Cok et al.	
2018/0033853	A1	2/2018	Bower et al.	
2018/0041005	A1	2/2018	Bower et al.	

FOREIGN PATENT DOCUMENTS

EP	2078978	A2	7/2009
EP	2148264	A2	1/2010
EP	2 610 314	A1	7/2013
EP	2703969	A2	3/2014
JP	11-142878		5/1999
WO	WO-2006/027730	A1	3/2006
WO	WO-2006/099741	A1	9/2006
WO	WO-2008/103931	A2	8/2008
WO	WO-2010/032603	A1	3/2010
WO	WO-2010/132552	A1	11/2010
WO	WO-2013/064800	A1	5/2013
WO	WO-2014/121635	A1	8/2014
WO	WO-2014/149864	A1	9/2014
WO	WO-2015/088629	A1	6/2015
WO	WO-2015/193434	A2	12/2015
WO	WO-2016/030422	A1	3/2016
WO	WO-2016/046283	A2	3/2016
WO	WO-2017/042252	A1	3/2017
WO	WO-2017/060487	A2	4/2017
WO	WO-2017/149067	A1	9/2017
WO	WO-2017/174632	A1	10/2017

OTHER PUBLICATIONS

International Search Report, PCT/EP2015/063709, dated Dec. 15, 2015, 6 pages.

International Search Report, PCT/EP2015/069553, dated Nov. 27, 2015, 6 pages.

Lee, S. H. etal, Laser Lift-Offof GaN Thin Film and its Application to the Flexible Light Emitting Diodes, Proc. of SPIE 8460:846011-1-846011-6 (2012).

Roscher, H., VCSEL Arrays with Redundant Pixel Designs for 10Gbits/s 2-D Space-Parallel MMF Transmission, Annual Report, optoelectronics Department, (2005).

Yaniv et al., A 640×480 Pixel Computer Display Using Pin Diodes with Device Redundancy, 1988 International Display Research Conference, IEEE, CH-2678-1/88:152-154 (1988).

U.S. Appl. No. 14/788,632, filed Jun. 30, 2015, X-Celeprint Limited.

U.S. Appl. No. 14/807,311, filed Jul. 23, 2015, X-Celeprint Limited.

U.S. Appl. No. 14/822,866, filed Aug. 10, 2015, Bower et al.

Cok, R. S. et al., AMOLED displays with transfer-printed integrated circuits, Journal of SID 19/(4):335-341 (2011).

Hamer et al., "63.2: AMOLED Displays Using Transfer-Printed Integrated Circuits," SID 09 Digest, 40(2):947-950 (2009).

Johnson, K. et al., Advances in Red VCSEL Technology, Advances in Optical Technologies, 2012:569379, 13 pages. (2012).

Kasahara, D. et al, Nichia reports first room-temperature blue/'green' VCSELs with current injection, Appl. Phys. Express, 4(7):3 pages (2011).

Koma, N. et al., 44.2: Novel Front-light System Using Fine-pitch Patterned OLED, SID, 08:655-658 (2008).

Seurin, J.F. et al, High-power red VCSEL arrays, Proc. of SPIE 8639:1-9 (2013).

Yoon, J. et al., Heterogeneously Integrated Optoelectronic Devices Enabled by MicroTransfer Printing, Adv. Optical Mater. 3:1313-1335 (2015).

(56) **References Cited**

OTHER PUBLICATIONS

Choi, H. W. et al., Efficient GaN-based Micro-LED Arrays, Mat. Res. Soc. Symp. Proc. 743:L6.28.1-L6.28.6 (2003).
Poher, V. et al., Micro-LED arrays: a tool for two-dimensional neuron stimulation, J. Phys. D: Appl. Phys. 41:094014 (2008).
U.S. Appl. No. 14/822,868, Bower et al.

* cited by examiner

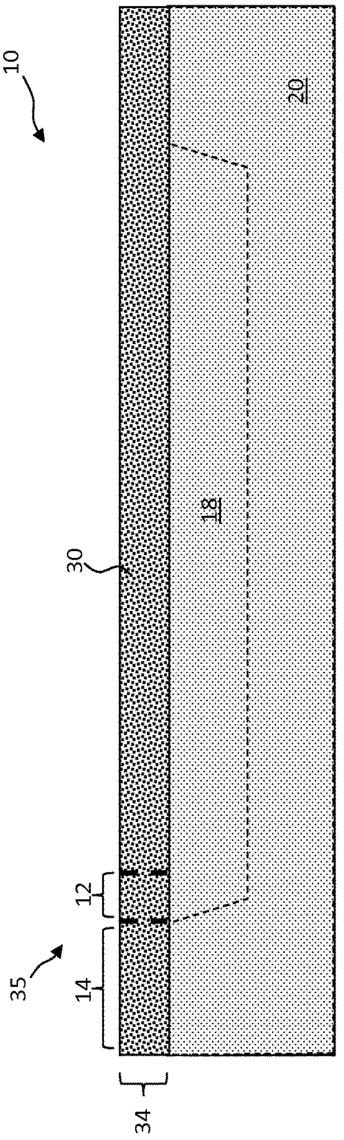


FIG. 1A

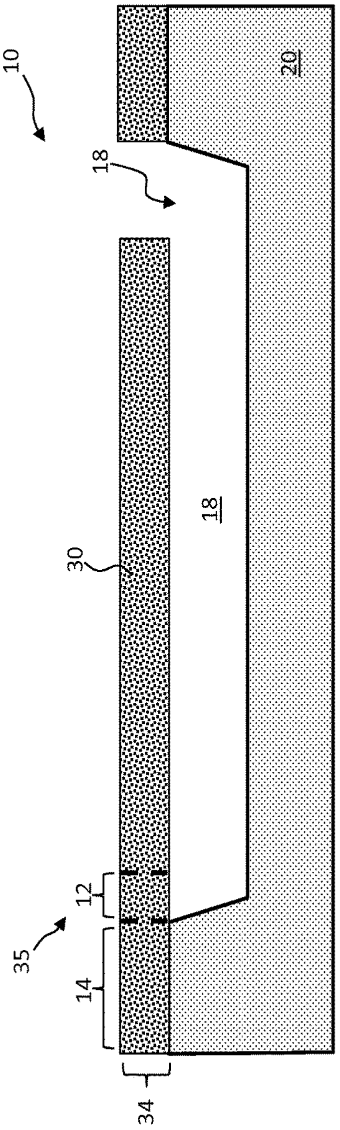


FIG. 1B

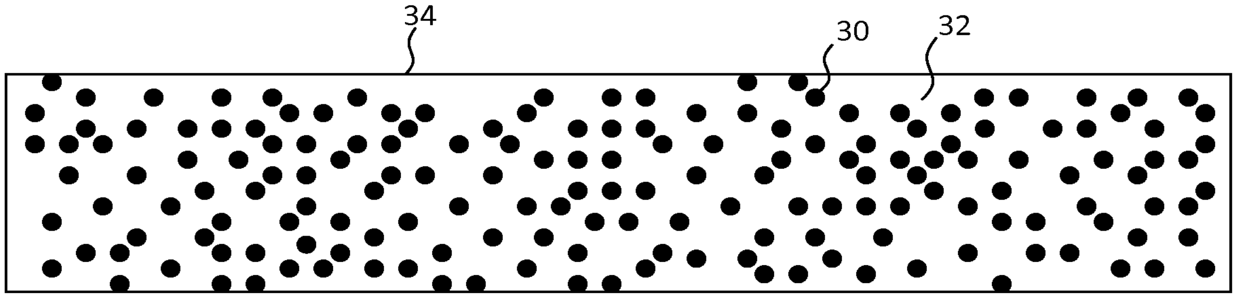


FIG. 2

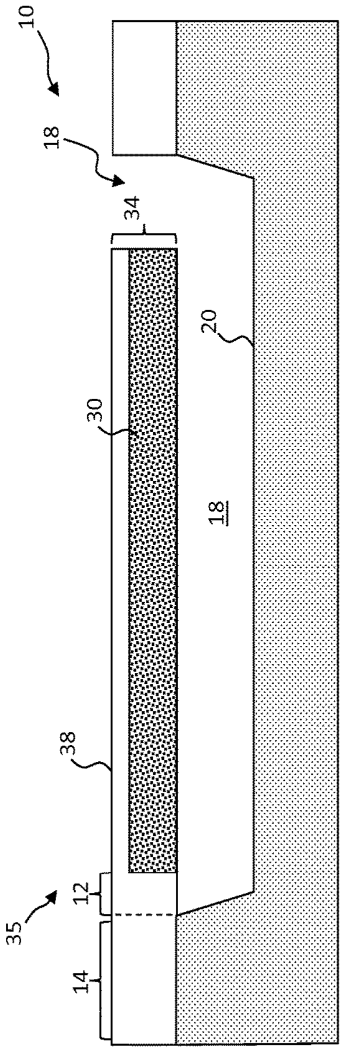


FIG. 3

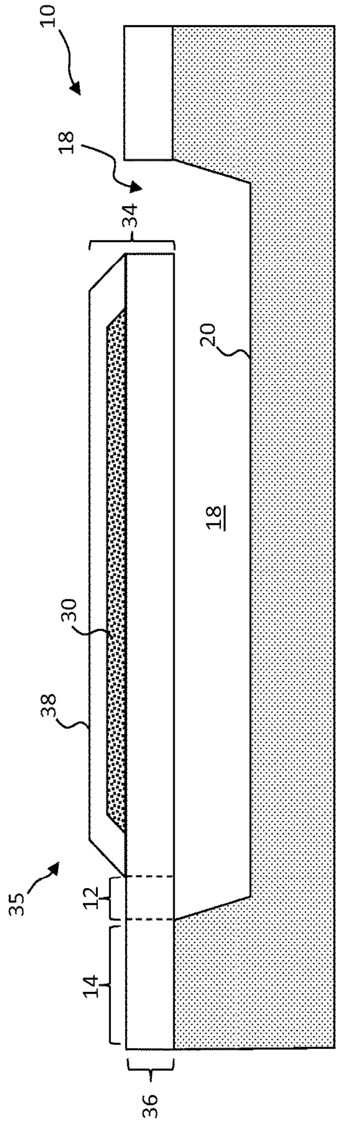


FIG. 4

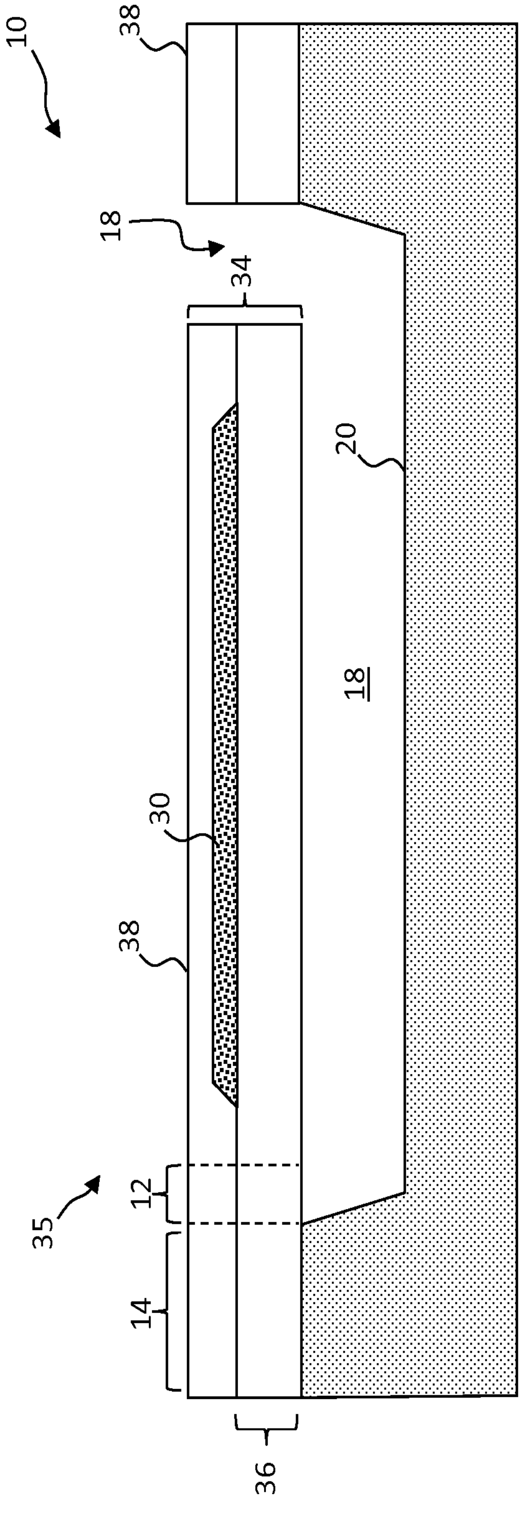


FIG. 5

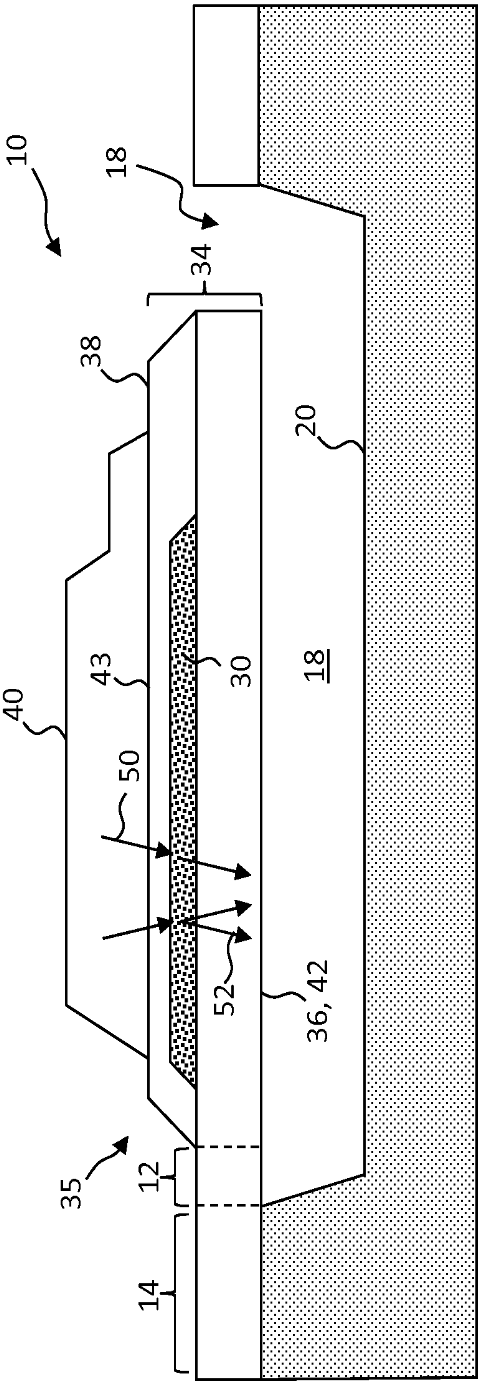


FIG. 6

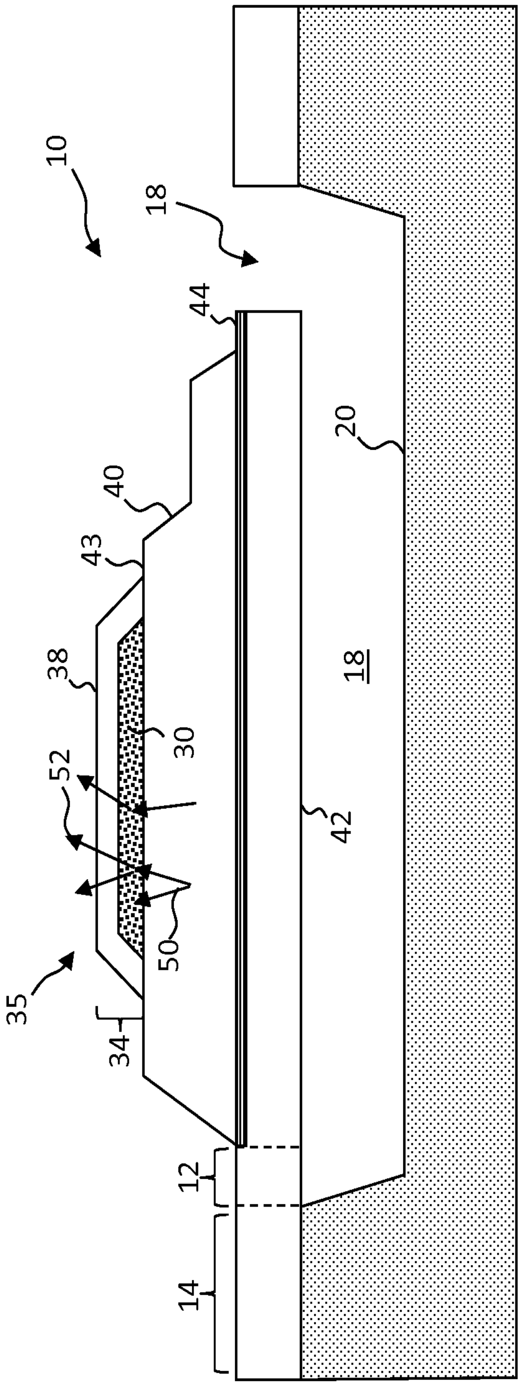


FIG. 7

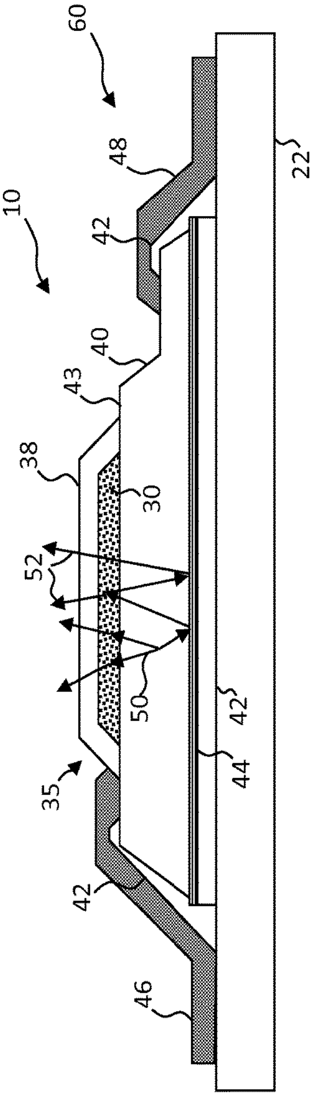

10
60
48
42
22
40
43
38
30
52
50
42
44
35
42
46

FIG. 8

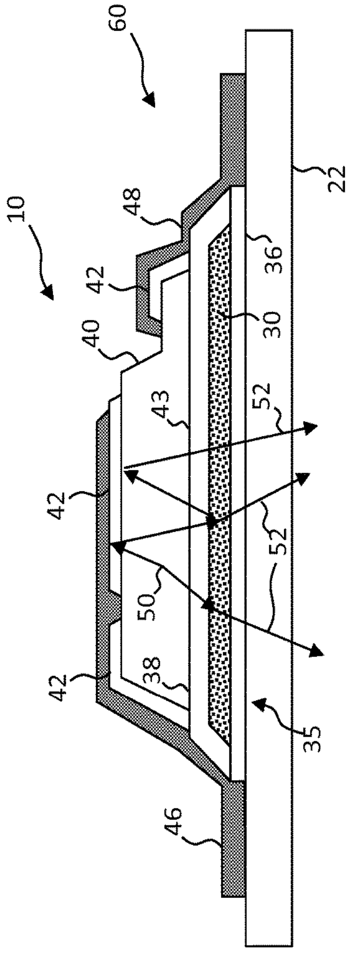

60
10
48
22
42
36
40
30
43
52
42
52
50
38
42
35
46

FIG. 9

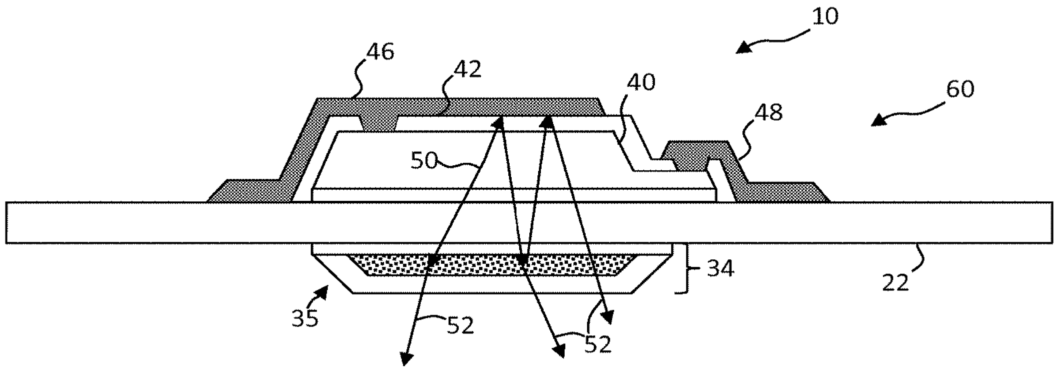

10
46
42
40
60
48
50
34
22
35
52
52

FIG. 10

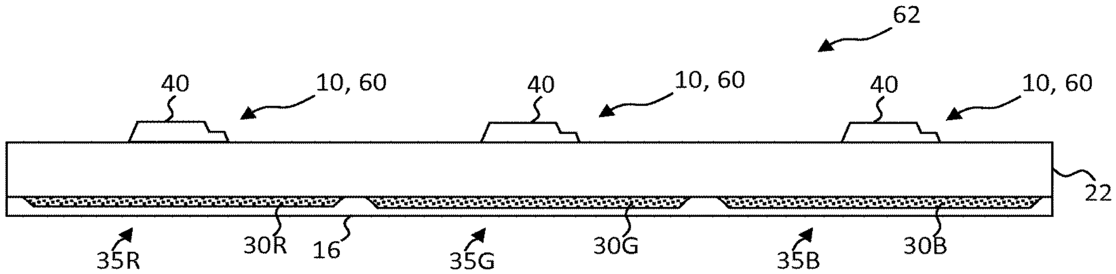

62
40
10, 60
40
10, 60
40
10, 60
22
35R
30R
16
35G
30G
35B
30B

FIG. 11

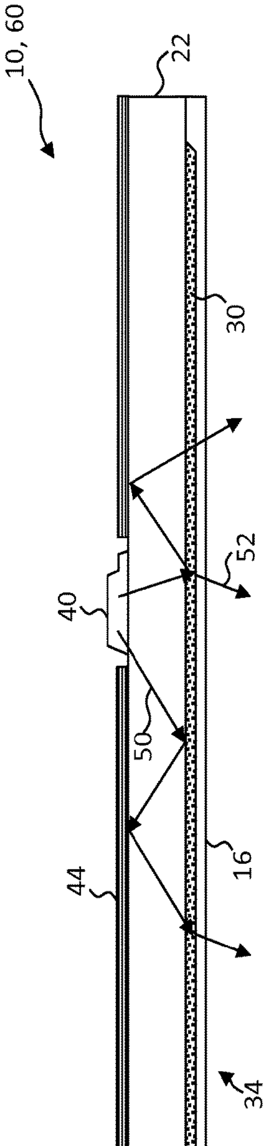


FIG. 12

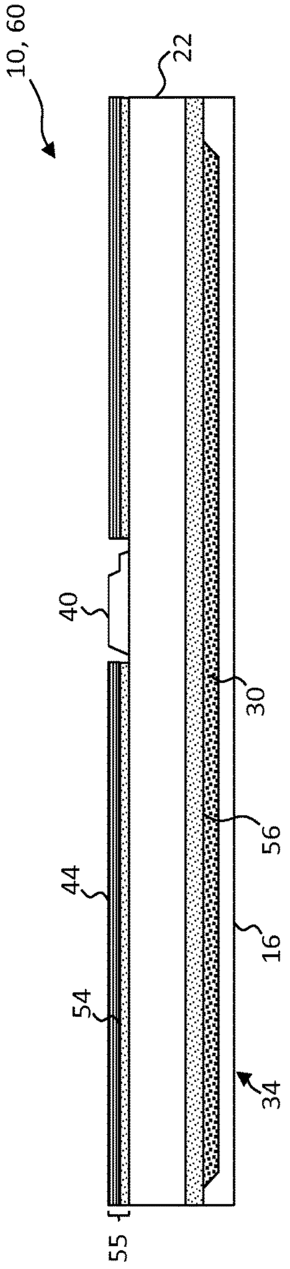


FIG. 13

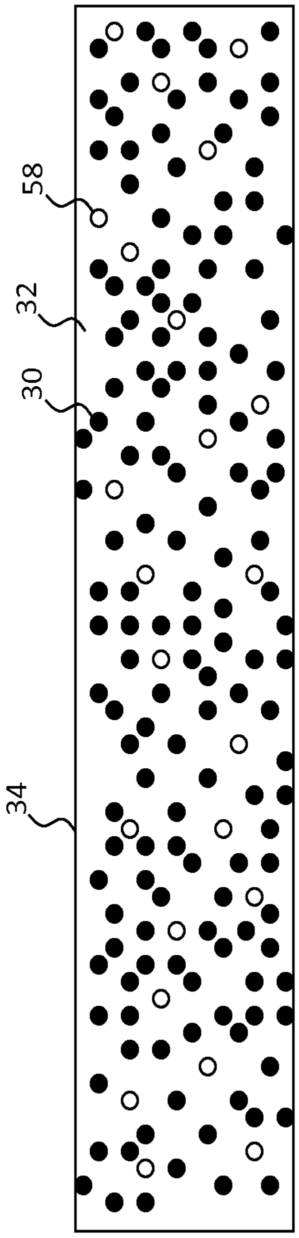


FIG. 14

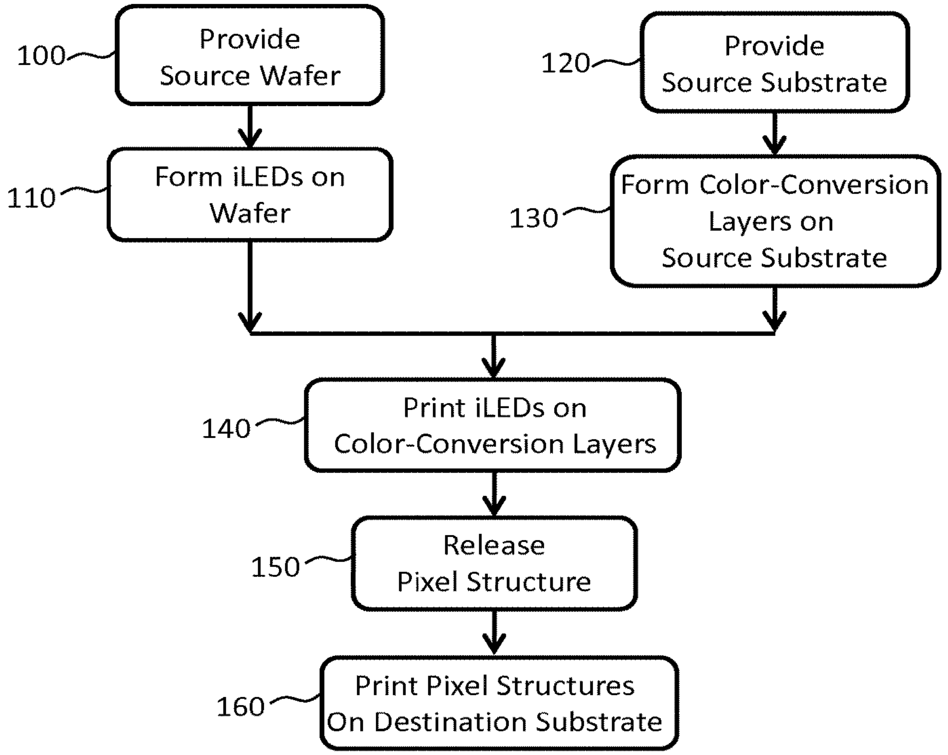

100
Provide Source Wafer
110
Form iLEDs on Wafer
120
Provide Source Substrate
130
Form Color-Conversion Layers on Source Substrate
140
Print iLEDs on Color-Conversion Layers
150
Release Pixel Structure
160
Print Pixel Structures On Destination Substrate

FIG. 15


141
Print Color-Conversion Layers On iLEDs

FIG. 16

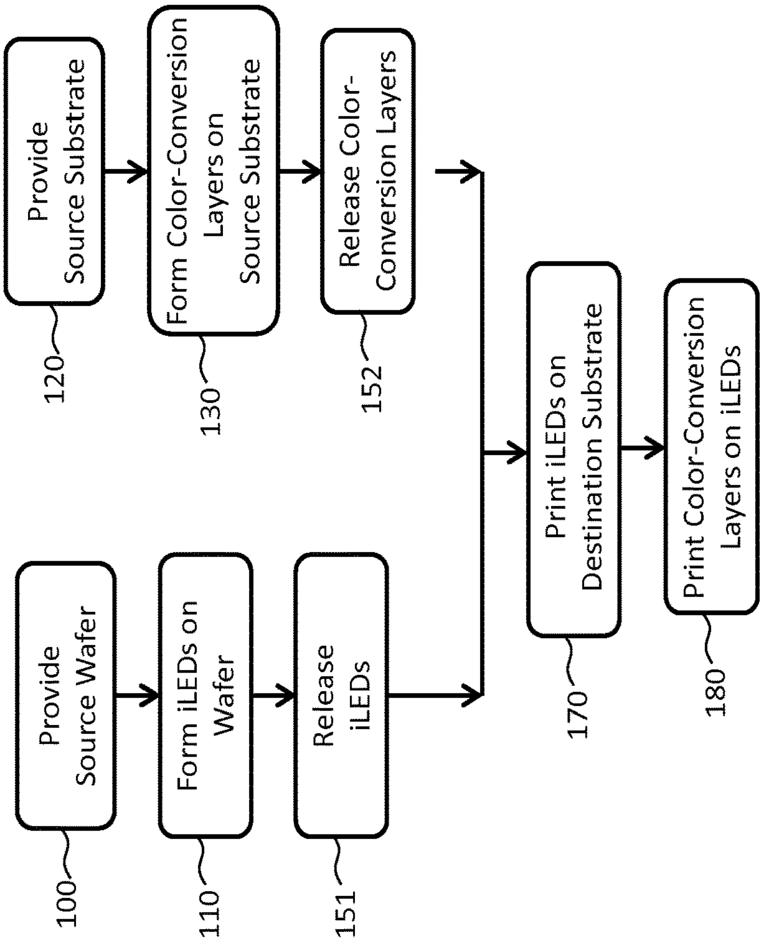

Provide Source Wafer
100
Form iLEDs on Wafer
110
Release iLEDs
151
Provide Source Substrate
120
Form Color-Conversion Layers on Source Substrate
130
Release Color-Conversion Layers
152
Print iLEDs on Destination Substrate
170
Print Color-Conversion Layers on iLEDs
180

FIG. 17

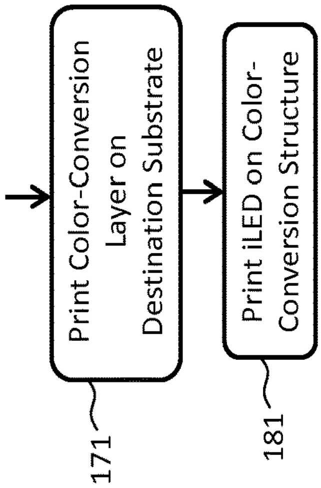

Print Color-Conversion Layer on Destination Substrate
171
Print iLED on Color-Conversion Structure
181

FIG. 18

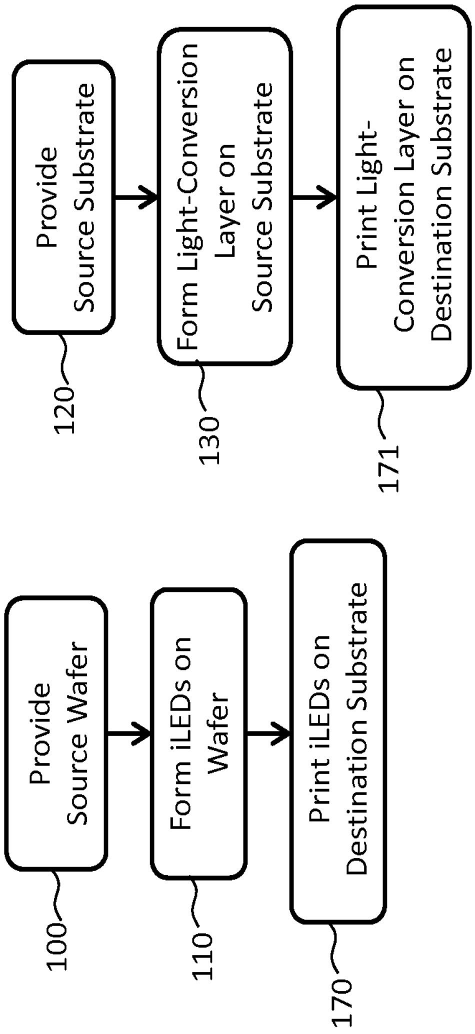

Provide Source Wafer
100
Form iLEDs on Wafer
110
Print iLEDs on Destination Substrate
170
Provide Source Substrate
120
Form Light-Conversion Layer on Source Substrate
130
Print Light-Conversion Layer on Destination Substrate
171

FIG. 19

DISPLAY WITH COLOR CONVERSION

CROSS REFERENCE TO RELATED APPLICATION

This application is related to commonly assigned U.S. patent application Ser. No. 14/743,940 filed Jun. 18, 2015, entitled Micro-Assembled LED Displays and Lighting Elements, which is hereby incorporated by reference in its entirety.

FIELD OF THE INVENTION

The present invention relates to displays having color-conversion materials such as phosphors or quantum dots that are excited by light having a higher frequency and radiate light having a lower frequency and light diffusers. More particularly, light excitation is provided by a light-emitting diode or light-emitting-diode laser.

BACKGROUND OF THE INVENTION

Conventional cathode ray tube (CRT) displays rely on an electron beam that sweeps over a phosphor-coated display surface on the inside of the tube to form an image. Different phosphors are stimulated by the high-energy electrons to emit different colors of light, for example red, green, and blue corresponding to pixels in the displayed image. Phosphors are also commonly used with solid-state light-emitting diodes to emit white light. For example, a blue-light emitting diode (LED) coated with phosphors that absorb a portion of the emitted blue light and emitted yellow light appears white to the human visual system. Similarly, organic light-emitting diode (OLED) illumination devices using phosphors are described in WO 2010032603.

Flat-panel light-emitting diode (LED) displays that incorporate luminescence-converting elements (such as phosphors) are described in U.S. Pat. No. 5,994,722. Alternatively, OLED displays can employ a single high-frequency light emitter together with color-conversion materials (also known as color-change materials) to provide a variety of color light output. The color-conversion materials absorb the high-frequency light and re-emit light at lower frequencies. For example, an LED or OLED device can emit blue light suitable for a blue sub-pixel and employ a green color-conversion material layer to absorb the blue light to emit green light and employ a red color-conversion material layer to absorb the blue light to emit red light. The color-conversion materials can be combined with color filters to further improve the color of the emitted light and to absorb incident light and avoid exciting the color-conversion materials with ambient light, thereby improving device contrast. Light-scattering phosphorescent or fluorescent particles excited by organic light-emitting diodes (OLEDs) are described in U.S. Pat. No. 7,834,541. U.S. Patent Pub. No. 20050116621 A1 entitled Electroluminescent devices and methods of making electroluminescent devices including a color conversion element also describes the use of color-conversion materials.

Layers having color-conversion materials can be combined with scattering particles to enhance the performance of the color-conversion materials by increasing the likelihood that incident light will interact with the color-conversion materials, thereby reducing the concentration or thickness of the layer. Such a combination may also prevent light emitted by the color-conversion material from being trapped in the color-conversion material layer. U.S. Pat. No. 7,791,271 describes a top-emitting OLED with color conversion materials and U.S. Pat. No. 7,969,085 discloses a color change material layer. U.S. Patent Pub. No. 20050275615 A1 entitled Display device using vertical cavity laser arrays describes such a layer as does U.S. Patent Pub. No. 20040252933 entitled Light Distribution Apparatus. U.S. Patent Pub. No. 20050012076 entitled Fluorescent member, and illumination device and display device including the same teaches the use of color-conversion materials as scattering particles. U.S. Patent Pub. No. 20040212296 teaches the use of scattering particles in a color-conversion material layer to avoid trapping the frequency-converted light. Diffusers are also useful in increasing the viewing angle of display pixels. U.S. patent application Ser. No. 11/361,094, filed Feb. 24, 2006, entitled Light-Scattering Color-Conversion Material Layer describes integral light-scattering color-conversion material layers.

Flat-panel displays typically rely on thin-film semiconductor structures to provide control signals that control the pixels in the flat-panel display. However, such thin-film structures have relatively low performance when compared to crystalline semiconductor structures typically used in integrated circuits. Furthermore, LED emitters, and especially micro-LED emitters have a relatively small light-emitting area and aperture ratio when used in flat-panel displays. Color-conversion layers coated over an entire flat-panel substrate are therefore wasteful since most of the layer is not excited by light-emission from the LEDs. Patterning the substrate at the resolution needed with micro-LEDs is difficult and the use of larger LEDs that are individually coated with color-conversion material limits the resolution of the flat-panel display.

There is a need, therefore, for devices, systems and methods for providing color-conversion structures in combination with micro-LEDs in a flat-panel display that enable high resolution, effective use of color-conversion material, and excellent performance efficiency, viewing angle, and colors.

SUMMARY OF THE INVENTION

Embodiments of the present invention provide a flat-panel display with improved electrical performance, improved optical performance, simplified structures, and reduced costs. In one aspect, the present invention provides a micro-transfer printable color-conversion structure that can be micro-transfer printed to a destination or display substrate. Micro-light-emitting diodes (micro-LEDs or μLEDs) are also micro-transfer printed to the same substrate and disposed so that some light emitted from the μLEDs at a relatively higher frequency is absorbed by the color-conversion structure and re-emitted at a relatively lower frequency. Arrays of different color-conversion structures can include different color-conversion materials that emit light of different colors, for example red, green, and blue, providing pixels in a full-color display.

Micro-light-emitting diodes can be micro-transfer printed onto a micro-transfer printable color-conversion structure to form a heterogeneous pixel structure (a heterogeneous structure has different kinds of elements making up a pixel device or a portion of a pixel device that emits light to provide a display pixel). The heterogeneous pixel structure can be micro-transfer printed as a unit onto a substrate. Alternatively, the color-conversion structures are micro-transfer printed onto the micro-light-emitting diodes to form a pixel structure that can be micro-transfer printed as a single unit onto a substrate. In other embodiments, the micro-light-emitting diodes and color-conversion structures are separately micro-transfer printed onto the substrate to provide the display pixels. Diffusers and reflectors can be included to increase the efficiency of the pixel structures in the display.

By providing micro-transfer printable color-conversion structures on a source substrate at higher density and with a larger fill factor than on a display substrate, the amount of color-conversion material wasted is reduced. The percentage of the source substrate that is dedicated to color-conversion structures is much greater than for a display substrate, particularly because the light-emissive area of the micro-LEDs and the consequent aperture ratio of the display substrate is relatively small. Thus, a greater percentage of the color-conversion material is applied to the color-conversion structures in a coating on the source substrate than in a coating on the display substrate so that less color-conversion material is wasted in the source substrate coating than is wasted in the display substrate coating.

Local pixel controllers can also be included in each pixel structure to provide active-matrix control. The pixel controllers together with the micro-LEDs and the color-conversion structures can be constructed in a compound micro assembly structure, for example forming a display tile on a tile substrate. The display tiles can be surface-mountable structures that are readily manipulated, printed, or interconnected on a display substrate using established surface mount technology techniques. Alternatively, the tiles can be micro-transfer printable to a display substrate.

The micro-light-emitting diodes can be made using crystalline semiconductors in a semiconductor wafer and then micro-transfer printed to a display substrate, for example a glass substrate, thus increasing the light-output efficiency and resolution of the micro-LEDs and reducing the substrate and assembly cost. Not all colors of light are emitted with equal efficiency by micro-LEDs. Therefore, a single type of high-efficiency micro-LED that emits blue, violet, or ultra-violet light that is absorbed by the different color-conversion structures making up each pixel in a display enables differently colored saturated light output with improved efficiency. In one embodiment, the micro-LEDs are solid-state organic or inorganic micro-LED lasers.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and other objects, aspects, features, and advantages of the present disclosure will become more apparent and better understood by referring to the following description taken in conjunction with the accompanying drawings, in which:

FIGS. **1**A and **1**B are cross sections of color-conversion structure in an embodiment of the present invention;

FIG. **2** is a detail cross section of FIG. **1**;

FIG. **3** is a cross section of a patterned color-conversion structure in an alternative embodiment of the present invention;

FIGS. **4** and **5** are cross sections of alternative encapsulated color-conversion structures in other embodiments of the present invention;

FIGS. **6** and **7** are cross sections of alternative arrangements of a color-conversion structure and an inorganic light-emitting diode in alternative embodiments of the present invention;

FIGS. **8**, **9**, and **10** are cross sections of various pixel structures in various embodiments of the present invention;

FIG. **11** is a cross section of a color display in an embodiment of the present invention;

FIGS. **12** and **13** are cross sections of various pixel structures including a reflector in various embodiments of the present invention;

FIG. **14** is a cross section of a color-conversion structure having light diffusers according to various embodiments of the present invention; and

FIGS. **15-19** are flow diagrams illustrating methods in various embodiments of the present invention.

The features and advantages of the present disclosure will become more apparent from the detailed description set forth below when taken in conjunction with the drawings, in which like reference characters identify corresponding elements throughout. In the drawings, like reference numbers generally indicate identical, functionally similar, and/or structurally similar elements. The figures are not drawn to scale since the variation in size of various elements in the Figures is too great to permit depiction to scale.

DETAILED DESCRIPTION OF THE INVENTION

Referring to the cross sections of FIG. **1**A and FIG. **1**B, in an embodiment of the present invention a color-conversion structure **10** comprises an article **35** (i.e., a color-conversion article) including a color-conversion material **30** disposed within a color-conversion layer **34** that can include multiple sub-layers. In the example shown in FIGS. **1**A and **1**B, the color-conversion layer is unpatterned. The unpatterned color-conversion layer **34** of FIG. **1** can be disposed on the source substrate **20** by first forming a liquid mixture including the color-conversion materials **30** in a curable liquid (e.g., a resin coating) that can be applied to the source substrate by, for example, spin coating the mixture over the source substrate, and then curing the mixture to form the color-conversion layer **34**. Alternatively, evaporation, sputtering, or sprinkling methods can be used.

At least a portion of a tether **12** is connected to the article **35** and extends or protrudes from the article **35**, for example from a periphery, edge or side of the article **35**. The color-conversion structure **10** can be attached with the tether **12** to an anchor **14** of a source substrate **20** (e.g., a native substrate on which the color-conversion structure **10** is formed). The anchor **14** can be a portion of the source substrate **20** to which a tether **12** is attached. In one configuration, the source substrate **20** has one or more sacrificial portions **18** and a corresponding color-conversion structure **10** is disposed or formed on or over each sacrificial portion **18** of the source substrate **20**. The sacrificial portion **18** can be a designated area or portion of the source substrate **20** (e.g., as in FIG. **1**A), a sacrificial material layer, a portion of a sacrificial material layer, a patterned sacrificial material layer, or a cavity under the color-conversion structure **10**, for example formed by removing a portion or all of a sacrificial material layer. As shown in FIG. **1**B, the sacrificial portion **18** is a cavity above which the color-conversion structure **10** is suspended by the tether **12** affixed to the anchor **14** so that the tether **12** extends from a periphery of the sacrificial portion **18** (at an anchor **14**) to a periphery of the color-conversion structure **10**. According to an embodiment of the present invention, the color-conversion structure **10** can be micro-transfer printed.

As shown in FIG. **2**, in one embodiment of the present invention, the color-conversion layer **34** includes color-conversion material **30** disposed within a transparent matrix **32**. For example, the transparent matrix can be a resin, a polymer, or a curable resin. The source substrate **20** can be a semiconductor source substrate **20**, for example silicon, such as silicon (1 0 0) or silicon (1 1 1), glass, plastic, or other materials suitable for wafers. Sacrificial layers or sacrificial portions **18** can include layers or patterned layers of etchable materials, for example such as oxides or nitrides such as silicon oxide or silicon nitride, or portions of the source substrate **20** that are differentially etchable in different directions (for example by taking advantage of the crystalline structure of the source substrate **20** to etch in one direction more rapidly than in another direction).

As intended herein, an optical-conversion structure **10** includes color-conversion materials **30** that redirect or re-emit light emitted from a light source, such as an organic light-emitting diode (OLED) or an inorganic light-emitting diode (iLED) or LED laser. A color-conversion material **30** is any material that absorbs electromagnetic radiation of a relatively higher frequency and emits electromagnetic radiation of a relatively lower frequency. The higher frequency electromagnetic radiation can be visible light, ultra-violet radiation, or infrared radiation. The higher-frequency electromagnetic radiation can be blue or violet visible light. The lower-frequency electromagnetic radiation can also be visible, ultra-violet radiation, or infrared radiation. According to one embodiment of the present invention, the higher frequency radiation is ultra-violet, violet, or blue and the lower frequency electromagnetic radiation is visible light, such as blue, cyan, green, yellow, orange, or red light. The color-conversion material **30** can include one or more of an inorganic phosphor, an organic phosphor, a ceramic phosphor, an inorganic fluorophore, an organic fluorophore, yttrium aluminum garnet, doped yttrium aluminum garnet, cesium-doped yttrium aluminum garnet (YAG), yttrium phosphate-vanadate, and a quantum dot.

According to a further embodiment of the present invention, the source substrate has one or more sacrificial portions **18**, for example forming an array of sacrificial portions **18** over, on, or in the source substrate **20**. Each sacrificial portion **18** has a color-conversion layer **34** disposed on or over each of the sacrificial portions **18**. In each case, a tether **12** extends from an anchor **14** (e.g., from a periphery of the sacrificial portion **18**) to a periphery of the color-conversion structure **10** to connect the color-conversion structure **10** to the source substrate **20**. The array of color-conversion structures **10** can be micro-transfer printed from the source substrate **20** to a destination substrate **22** (e.g., a display substrate **22**) as is described further below and, for example, in U.S. patent application Ser. No. 14/743,981, filed Jun. 18, 2015, entitled Micro Assembled LED Displays and Lighting Elements, which is hereby incorporated by reference in its entirety.

In FIG. **1**, the color-conversion layer **34** is not patterned and the anchor **14** and tether **12** both include color-conversion material **30**. Referring to FIG. **3**, in an alternative embodiment the color-conversion material **30** or color-conversion layer **34** is patterned over the sacrificial portions **18**. In the alternative embodiment of FIG. **3**, neither the anchor **14** nor the tether **12** include the color-conversion material **30**.

The patterned color-conversion layer **34**, as shown in FIG. **3**, can be formed by photolithographically processing a blanket-coated layer of color-conversion materials **30** in a photo-curable matrix, such as a photoresist, exposing the blanket-coated layer of color-conversion materials **30** to patterned electro-magnetic radiation (e.g., ultra-violet light through a patterned mask), and then developing the pattern-wise exposed coating. The patterned color-conversion layer **34** forms a first layer and a second layer **38** of material that does not include color-conversion material **30** can be coated over the patterned color-conversion layer **34** to form the tether **12** and anchor **14** of FIG. **3**.

Referring to FIG. **4**, in another embodiment, the color-conversion layer **34** further includes a first layer **36** on which the color-conversion material **30** is disposed and a second layer **38** that is disposed on the color-conversion material **30** so that the first layer **36** and second layers **38** encapsulate the color-conversion materials **30**. The first layer **36**, the color-conversion material **30**, and the second layer **38** form the color-conversion layer **34**. In this embodiment, the color-conversion materials **30** can be provided in a transparent matrix **32** (not shown, as in FIGS. **1-3**) or in a layer deposited on the first layer **36**. The layer can be very thin, for example a few nanometers or less, or relatively thick, for example 10-100 microns or more and can be deposited by evaporation, by spray coating, by sputtering, or by sprinkling. The embodiment of FIG. **4** is useful for color-conversion structures **10** in which the transparent matrix **32**, for example curable liquids, can damage or otherwise inhibit the performance of the color-conversion materials **30**.

As illustrated in FIG. **5**, the first layer **36** is coated over the entire source substrate and is therefore a portion of the tether **12** and anchor **14**. As shown in FIG. **5** and as in FIG. **3**, the second layer **38** can also be coated over the entire source substrate **20** so that the second layer **38** also makes up a portion of the tether **12** or anchor **14**.

In an embodiment of the present invention, the first layer **36** is transparent, the second layer **38** is transparent, or both the first layer **36** and the second layer **38** are transparent. In another embodiment, the first layer **36** is reflective and the second layer **38** is transparent. In yet another embodiment, the second layer **38** is reflective and the first layer **36** is transparent. Transparent materials can include photoresist materials, such as SU8 or other resins, epoxies, polymers, or glasses that can be coated in a liquid state and cured or laminated over and adhered to layers. Reflective layers can include metals such as silver or aluminum that can be evaporated or laminated onto a surface.

Referring to FIG. **6**, a color-conversion structure **10** of the present invention can include an organic or inorganic micro-light-emitting diode (micro-LED) **40** having a light-emitting side **43** disposed to emit light **50** toward the color-conversion material **30** in the article **35**. In one embodiment, the micro-LED **40** is a solid-state LED laser. Micro-LED **40** devices having various structures can be made using, for example, doped or undoped semiconductor materials and can be made using photolithographic techniques. An inorganic LED (iLED) or organic LED (OLED can be a micro-LED **40**. The term micro-LED **40** is used herein to generically refer to OLED or iLED devices that can also be LED lasers. The micro-LEDs **40** can be relatively small, for example in embodiments each micro-LED **40** has a width from 2 to 5 μm, 5 to 10 μm, 10 to 20 μm, or 20 to 50 μm, each micro-LED **40** has a length from 2 to 5 μm, 5 to 10 μm, 10 to 20 μm, or 20 to 50 μm, or each micro-LED **40** has a height from 2 to 5 μm, 4 to 10 μm, 10 to 20 μm, or to 50 μm. Similarly, in embodiments when placed on a display substrate **22**, the display substrate **22** has a contiguous display substrate area that includes the micro-LEDs **40**, each micro-LED **40** has a light-emissive area, and the combined light-emissive areas of the micro-LEDs **40** is less than or equal to one-quarter of the contiguous display substrate area or wherein the combined light-emissive areas of the micro-LEDs **40** is less than or equal to one eighth, one tenth, one twentieth, one fiftieth, one hundredth, one five-hundredth, one thousandth, one two-thousandth, or one ten-thousandth of the contiguous display substrate area. Furthermore, each micro-LED **40** has an anode and a cathode disposed on a same side of the respective micro-LED **40** and, optionally, the anode and cathode of a respective light emitter are horizontally separated by a horizontal distance, wherein the horizontal distance is from 100 nm to 500 nm, 500 nm to 1 micron, 1 micron to 20 microns, 20 microns to 50 microns, or 50 microns to 100 microns.

According to an embodiment of the present invention, the micro-LED **40** can emit higher-frequency light **50** that is absorbed by the color-conversion materials **30** in the color-conversion layer **34**. The color-conversion materials **30** then emit color-converted light **52** of a lower frequency than the higher-frequency absorbed light **50**. As illustrated in the embodiment of FIG. **6**, the article **35** including the color-conversion material **30** is located between the micro-LED **40** and the sacrificial portion **18** on the source substrate **20**. In the embodiment of FIG. **6**, the micro-LED **40** can be constructed on the article **35** using photolithographic processes. In an alternative method, a previously constructed micro-LED **40** formed on another source substrate different from the source substrate **20** can be micro-transfer printed onto the color-conversion layer **34** to form the color-conversion structure **10** of FIG. **6**. The micro-LED **40** can be constructed or printed on the article **35** before the sacrificial layer **18** is removed or a cavity formed beneath the article **35**.

In a different embodiment shown in FIG. **7**, the micro-LED **40** is located between the color-conversion material **30** and the sacrificial portion **18**. In the structure of FIG. **7**, the second layer **38** is transparent and the micro-LED **40** serves as the first layer **36** found in FIGS. **4** and **5**. In the embodiment of FIG. **7**, the color-conversion layer **34** can be constructed on the micro-LED **40** using photolithographic processes. In an alternative method, a previously constructed color-conversion layer **34** formed on a source substrate different from the source substrate **20** can be micro-transfer printed onto the micro-LED to form the color-conversion structure **10** of FIG. **7**. The color-conversion layer **34** can be constructed or printed on the micro-LED **40** before the sacrificial layer **18** is removed or a cavity formed beneath the micro-LED **40**.

Referring to FIG. **8** and according to various embodiments, the color-conversion structure **10** of FIG. **7** can be disposed on a destination substrate **22**, for example by micro-transfer printing, and at least a portion of a tether **12** is a broken or fractured tether **12** (not shown). As shown in FIG. **8**, the color-conversion structure **10** (including the article **35** and the micro-LED **40**) is disposed on the destination substrate **22** to form a pixel structure **60**. The micro-LED **40** has a light-emitting side **43** disposed to emit light **50** to the color-conversion material **30**. In the embodiment of FIG. **8**, the micro-LED **40** is located between the article **35** and the destination substrate **22**. The destination substrate **22** can be opaque or reflective. An array of such pixel structures **60** can be used to form a display and the destination substrate **22** can be a display substrate **22** (e.g., common to each pixel structure **60**). The embodiment of FIGS. **7** and **8** illustrates a top-emitting structure that emits light **50** from the pixel structure **60** in a direction opposite the destination substrate **22** on which the pixel structure **60** is disposed. In alternative arrangements, either of the pixel structures **60** of FIGS. **8** and **9** is disposed upside-down on the destination substrate **22** to emit light in the opposite direction as that indicated in FIGS. **8** and **9**. Such arrangements can be made using intermediate transfer stamps with micro-transfer printing and arrange the micro-LEDs **40** on a side of the color-conversion layer **34** opposite the destination substrate **22** (in contrast to FIG. **8**) or arrange the article on a side of the micro-LEDs **40** opposite the destination substrate **22** (in contrast to FIG. **9**).

In addition to the micro-LED **40** on which the article **35** is located, an optional reflective structure **44** such as a reflective layer is disposed between the micro-LED **40** and the destination substrate **22**. Alternatively, the destination substrate **22** can be reflective. If present, the reflective structure **44** serves to reflect light **50** emitted from the micro-LED **40** toward the destination substrate **22** to the color-conversion layer **34**. The reflective structure **44** can be a metal layer, for example a metal such as silver or aluminum, or other metals or reflective materials evaporated or laminated onto either the destination substrate **22** or the micro-LED **40**. Alternating layers of materials having different refractive indices can also be used to form a reflector for light having desired wavelengths. The reflective structure **44** can be electrically conductive or electrically insulating. If the reflective structure **44** is electrically conductive, the reflective structure **44** can spread current provided to the micro-LED **40**. If the reflective structure **44** is not present and if the destination substrate **22** is transparent to the light **50** emitted from the micro-LED **40**, light **50** emitted from the micro-LED **40** can pass through the destination substrate **22**.

The micro-LED **40** is provided with electrical current through first and second electrodes **46**, **48**. The first and second electrodes **46**, **48** are electrically connected to the micro-LED **40** at desired locations, as shown, and electrically insulated from the edges of the micro-LED **40** by dielectric layers **42** (for example oxides such as silicon dioxide). By electrically connecting the first and second electrodes **46**, **48** at desired locations, the location of hole and electron recombination in the micro-LED **40** is controlled to optimize light emission from the micro-LED **40**.

The pixel structure **60** of FIG. **8** is operated by providing an electrical current between the first and second electrodes **46**, **48**. Current flows within the micro-LED **40**, causing the micro-LED **40** to emit light **50** at a pre-determined frequency. Some of the light **50** is emitted toward the color-conversion material **30**; other light **50** is emitted toward the reflective structure **44** (if present) and is reflected back toward the color-conversion material **30**. The color-conversion material **30** absorbs at least some of the micro-LED-emitted light **50** and emits color-converted light **52** having a frequency lower than the micro-LED-emitted light **50**. Some of the color-converted light **52** emitted from the color-conversion material **30** is emitted in a direction toward the top of the pixel structure **60** and away from the destination substrate **22**, for example toward an observer (not shown). Other color-converted light **52** emitted from the color-conversion material **30** is emitted toward the destination substrate **22** and is reflected from the reflective structure **44** (if present) back toward the top of the pixel structure **60** and away from the destination substrate **22**. If the reflective structure **44** is not present and if the destination substrate **22** is transparent, the color-converted light **52** can pass through the destination substrate **22**. An electrode disposed on the bottom of the micro-LED between the micro-LED and the destination substrate **22** can be a non-reflective, transparent electrical conductor such as a transparent conductive oxide like indium tin oxide or aluminum zinc oxide enabling light to be emitted through the side of the micro-LED **40** adjacent to the destination substrate **22**.

Referring to FIG. **9**, and according to alternative embodiments, the color-conversion structure **10** of FIG. **6** can be disposed on a transparent destination substrate **22**, for example by micro-transfer printing, and at least a portion of a tether **12** is a broken or fractured tether **12** (not shown). As shown in FIG. **9**, the color-conversion structure **10** is disposed on the destination substrate **22** to form the pixel structure **60**. The micro-LED has a light-emitting side **43** disposed to emit light **50** to the color-conversion material **30**. In the embodiment of FIG. **9**, the color-conversion material **30** is located between the micro-LED **40** and the destination substrate **22**. The destination substrate **22** can be transparent. An array of such pixel structures **60** can be used to form a display and the destination substrate **22** can be a display substrate **22**. The embodiment of FIGS. **6** and **9** illustrates a bottom-emitting structure that emits light from the pixel structure **60** through the destination substrate **22** on which the pixel structure **60** is disposed. The first and second electrodes **46**, **48** that provide electrical current to the micro-LED **40** can also serve as reflectors that reflect emitted light **50** to the color-conversion layer **34**. The first and second electrodes **46**, **48** can be a metal, for example a metal such as silver or aluminum, or other metals or reflective materials evaporated or laminated onto the destination substrate **22** or the micro-LED **40**. Alternating layers of materials having different refractive indices can also be used to form a reflector for light having desired wavelengths independently of the first and second electrodes **46**, **48** if the first and second electrodes **46**, **48** do not adequately cover the micro-LED **40**.

The micro-LED **40** is provided with electrical current through first and second electrodes **46**, **48**. The first and second electrodes **46**, **48** are electrically connected to the micro-LED **40** at desired locations, as shown, and electrically insulated from the edges of the micro-LED **40** by dielectric layers **42** (for example oxides such as silicon dioxide). By electrically connecting the first and second electrodes **46**, **48** at desired locations, the location of hole and electron recombination in the micro-LED **40** is controlled to optimize light emission.

The pixel structure **60** of FIG. **9** is operated by providing an electrical current between the first and second electrodes **46**, **48**. Current flows within the micro-LED **40**, causing the micro-LED **40** to emit light **50** at a pre-determined frequency. Some of the light **50** is emitted toward the color-conversion material **30**; other light **50** is emitted toward the reflective first or second electrodes **46**, **48** (or other reflective structures) and is reflected back toward the color-conversion material **30**. The color-conversion material absorbs at least some of the micro-LED-emitted light **50** and emits color-converted light **52** having a frequency lower than the micro-LED-emitted light **50**. Some of the color-converted light **52** emitted from the color-conversion material **30** is emitted in a direction toward the bottom of the pixel structure **60** and through the destination substrate **22**, for example toward an observer (not shown). Other color-converted light **52** emitted from the color-conversion material **30** is emitted toward and reflected from the reflective first or second electrodes **46**, **48** (or other reflective structures) back toward the bottom of the pixel structure **60** and through the destination substrate **22**. If the reflective structures **44** are not present on the top of the micro-LED **40** (i.e., the side of the micro-LED **40** opposite the destination substrate **22**), the color-converted light **52** can pass through the top of the micro-LED **40**. For example, a non-reflective, transparent electrical conductor such as a transparent conductive oxide like indium tin oxide or aluminum zinc oxide can provide the first or second electrodes **46**, **48** enabling light to be emitted from the top of the micro-LED **40**.

Referring to the embodiment of FIG. **10**, a transparent substrate **22** (e.g., the destination or display substrate **22**), is located between the micro-LED **40** and the color-conversion material **30**. In this configuration, the micro-LED **40** functions as a bottom emitter and the color-conversion layer **34** functions as a top emitter. This structure enables the micro-LED **40** and the color-conversion layer **34** to be independently disposed on opposite sides of the transparent substrate **22**, facilitating manufacturing processes.

As in the configuration of FIG. **9**, in the embodiment of FIG. **10** the micro-LED **40** is provided with electrical current through first and second electrodes **46**, **48**. The first and second electrodes **46**, **48** are electrically connected to the micro-LED **40** at desired locations and electrically insulated from the edges of the micro-LED **40** by dielectric layers **42** (for example oxides such as silicon dioxide). By electrically connecting the first and second electrodes **46**, **48** at desired locations, the location of hole and electron recombination in the micro-LED **40** is controlled to optimize light emission.

The pixel structure **60** of FIG. **10** is operated by providing an electrical current between the first and second electrodes **46**, **48**. Current flows within the micro-LED **40**, causing the micro-LED **40** to emit light **50** at a pre-determined frequency. Some of the light **50** is emitted through the transparent substrate **22** toward the color-conversion material **30**; other light **50** is emitted toward the reflective first or second electrodes **46**, **48** (or other reflective structures) and is reflected back through the transparent substrate **22** toward the color-conversion material **30**. The color-conversion material **30** absorbs at least some of the micro-LED-emitted light **50** and emits color-converted light **52** having a frequency lower than the micro-LED-emitted light **50**. Some of the color-converted light **52** is emitted from the color-conversion material **30** is toward an observer. Other color-converted light **52** emitted from the color-conversion material **30** is emitted through the transparent substrate **22** toward and reflected from the reflective first or second electrodes **46**, **48** (or other reflective structures) back through the destination substrate **22**. If the reflective structures **44** are not present on the top of the micro-LED **40** (i.e., the side of the micro-LED **40** opposite the transparent substrate **22**), the color-converted light **52** can pass through the top of the micro-LED **40**. For example, a non-reflective, transparent electrical conductor such as a transparent conductive oxide like indium tin oxide or aluminum zinc oxide can provide the first or second electrodes **46**, **48** and enable the emission of color-converted light **52** (and light **50** emitted by the micro-LED **40**) through the top of the micro-LED **40**.

In the top-emitting configuration of FIGS. **7** and **8**, the bottom-emitting configuration of FIGS. **6** and **9**, and the alternative arrangement of FIG. **10**, the thickness of the color-conversion layer **34** and the density of the color-conversion materials **30** in the article **35** can be chosen so that both the micro-LED-emitted light **50** and the color-converted light **52** are emitted from the color-conversion structure **10**. Alternatively, the thickness of the color-conversion layer **34** and the density of the color-conversion materials **30** in the article **35** can be chosen so that substantially only the color-converted light **52** is emitted from the color-conversion structure **10**, for example 80%, 90%, 95%, or 98%. Since the micro-LED **40** and the color-conversion layer **34** are likely to have optical (refractive) indices greater than the optical index of air, the color-conversion structure **10** can include light extraction structures to increase the amount of light emitted from the color-conversion structure **10**.

A plurality of pixel structures **60** of the present invention can be provided in an array over a display substrate **22** to form a display. For example, an array of color-conversion structures **10** including micro-LEDs **40** can be disposed on the display substrate **22** and the micro-LEDs **40** interconnected using electrically conductive wires, such as metal wires, formed on the display substrate **22** to provide electrical current to the micro-LEDs **40** to emit light **50** that is color converted by the color-conversion materials **30**.

Referring to FIG. **11**, a plurality of micro-LEDs **40** are disposed in an array on the transparent display substrate **22** with red, green, and blue light-emitting color-conversion articles **35**R, **35**G, **35**B in the configuration of FIG. **10**. Different color-conversion materials **30**R, **30**G, **30**B are provided in different corresponding color-conversion articles **35**R, **35**G, **35**B that emit different colors of light **52**, for example red color-conversion article **35**R emits red light **52**, green color-conversion article **35**G emits green light **52**, and blue color-conversion article **35**B emits blue light **52**. Each of the three color-conversion structures **10** forms a pixel structure **60** that provides a pixel in a display **62**.

In one embodiment of the present invention, all of the micro-LEDs **40** emit light **50** having a frequency greater than the red, green, and blue light **52** emitted by the corresponding red, green, and blue color-conversion articles **35**R, **35**G, **35**B including the red, green, and blue color-conversion materials **30**R, **30**G, **30**B. In this embodiment, the micro-LEDs **40** pump each of the red, green, and blue color-conversion articles **35**R, **35**G, **35**B with the same frequency of micro-LED-emitted optical pump light, regardless of the color of light **52** emitted by the red, green, and blue color-conversion articles **35**R, **35**G, **35**B. In an alternative embodiment, a blue color-conversion article **35**B is not used and is replaced by a micro-LED **40** that emits blue light **50**. The blue-light-emitting micro-LEDs **40** can also be used to pump the red and green color conversion articles **35**R, **35**G. In this configuration, the micro-LEDs **40** all emit light **50** having a frequency greater than the green light **52**.

In a further embodiment of the present invention, an array of pixel structures **60** is complemented by an array of organic light-emitting diodes (OLEDs). This arrangement is useful if at least one of the colors of light in a pixel is more efficiently or inexpensively provided by an organic rather than an inorganic LED. For example, a red OLED can be provided together with a green- and a blue-light-emitting pixel structure **60** to form a full-color pixel in the display **62**.

The embodiments of FIGS. **6**-**9** illustrate pixel structures **60** including micro-LEDs and color-conversion layers **34** that can be micro-transfer printed in a single step from a source substrate **20** onto a destination substrate **22**. The embodiment of FIG. **10** enables micro-transfer printing the micro-LEDs **40** and color-conversion layers **34** independently. In these cases, the areas of the color-conversion layer **34** and the micro-LEDs **40** over the destination substrate **22** are similar, for example within a relative factor of two, four, or ten. Thus, in an embodiment of the present invention the micro-LED **40** has a light-emitting area, the color-conversion layer **34** or material **30** is patterned into light-emitting portions, and the area of the light-emitting portions is less than or equal to ten times the micro-LED light-emitting area, is less than or equal to four times the micro-LED light-emitting area, or is less than or equal to twice the micro-LED light-emitting area.

Referring again to FIG. **11**, in an alternative structure and method, the color-conversion layers **34** have an area over the destination substrate **22** that is much larger than the area of the micro-LEDs **40** over the destination substrate **22**, for example greater than a relative factor of two, four, or ten. Instead of micro-transfer printing the color-conversion articles **35**, the color-conversion layer **34** can be screen printed, evaporated through a shadow mask, deposited by inkjet, or otherwise deposited. Such an approach can be easier or less expensive than micro-transfer printing color-conversion articles **35** and can have larger features with a lower resolution. Thus, in another embodiment of the present invention the micro-LED **40** has a light-emitting area, the color-conversion layer **34** or material **30** is patterned into light-emitting portions, and the area of the light-emitting portions is greater than or equal to twice the micro-LED light-emitting area, is greater than or equal to four times the micro-LED light-emitting area, or is greater than or equal to ten times the micro-LED light-emitting area.

As shown in FIG. **11**, the color-conversion materials **30** and color-conversion layer **34** are encapsulated with an encapsulation layer **16** to protect the red, green, and blue color-conversion materials **30**R, **30**G, **30**B from environmental degradation. For example, organic color-conversion materials **30** can be susceptible to moisture.

Light emission from the various color-conversion structures **10** of the present invention can be enhanced with the use of diffusers that diffuse incident light, for example specular light propagating in a single direction, into diffuse light that propagates in a variety of directions. Because semiconductor materials found in micro-LEDs **40**, color-conversion materials **30**, or transparent matrix **32** materials can have optical refractive indices greater than the optical index of air and because the micro-LEDs **40** and color-conversion materials **30** are typically isotropic light emitters, emitted light can be trapped in the color-conversion structures **10** of the present invention due to total internal reflection. Light diffusers can modify the trajectory of trapped light and redirect it at an angle at which the light can escape.

According to an embodiment of the present invention and as illustrated in FIG. **12**, a reflective structure **44** is located on a common side of the transparent substrate **22** with the micro-LED **40**. The reflecting structure can be a reflector, a reflective structure **44**, a diffusive reflector **55** (FIG. **13**), or a diffusive reflective structure **44**. Diffuse reflectors can include metals with reflective particles or a metal-coated layer of particles having a size chosen to diffuse the wavelengths of light that are emitted by the micro-LEDs **40** and the color-conversion materials **30**. The diffuser can be disposed to diffuse light emitted by the micro-LEDs **40** before the light emitted by the micro-LEDs **40** is absorbed by the color-conversion material **30** in the color-conversion layer **34**. As shown in FIG. **12**, light **50** emitted by the micro-LED **40** can propagate in the transparent substrate **22** and then be redirected into the color-conversion article **35** and emitted from the color-conversion structure **10**. Light **52** emitted from the color-conversion article **35** that is trapped in the transparent substrate **22** can also be redirected and emitted from the color-conversion structure **10**.

As shown in FIG. **12**, the reflective structure **44** can be a diffusive reflective layer. Alternatively, as shown in FIG. **13**, a light-diffusive layer **56** can be disposed between the color-conversion layer **34** and the micro-LEDs **40** or located on a common side of the transparent substrate **22** with the micro-LEDs **40**, or both, as illustrated. For example, a light diffuser **54** can be incorporated into a reflective structure **44** to form a diffusive reflector **55**. As in FIG. **12**, light **50** emitted by the micro-LED **40** or light **52** emitted by the color-conversion layer **34** can propagate in the transparent substrate **22** and then be redirected into the color-conversion layer **34** and emitted from the color-conversion structure **10** by the light-diffusive layers **56**. Light-diffusive layers **56** can be transparent and include transparent particles having a refractive index different from a layer matrix, the transparent substrate **22**, or the color-conversion layer **34**. Light is diffused by refraction or reflection from the transparent particles. Alternatively, light-reflective particles can be included in the light-diffusive layers **56** to reflect and redirect light trapped in the transparent substrate **22**. In another embodiment of the present invention, referring to FIG. **14**, light-diffusive particles **58**, either transparent or reflective can be incorporated into the color-conversion layer **34**. The light-diffusive particles **58** can reflect or refract light **50** emitted by the micro-LEDs **40**, the light **52** emitted by the color-conversion materials **30**, or trapped light in the color-conversion layer **34**.

As noted above, with respect to FIG. **11**, a plurality of micro-LEDs **40** can be disposed in an array on the transparent display substrate **22** with red, green, and blue light-emitting color-conversion articles **35**R, **35**G, **35**B. Each of the three color-conversion structures **10** forms a pixel structure **60** that provides a pixel in a display **62**. Thus, a display **62** according to embodiments of the present invention can include a display substrate **22** and an array of color-conversion structures **10** disposed on the display substrate **22**. Each color-conversion structure **10** includes an inorganic light-emitting diode (micro-LED) **40** disposed to emit light **50** to color-conversion material **30** or an article **35** including color-conversion material **30** on the display substrate **22**. The array of color-conversion structures **10** can include an array of red color-conversion material **30**R that emits red light **52** and an array of green color-conversion material **30**G that emits green light **52** (collectively color-conversion material **30**). The array of color-conversion structures **10** can also include an array of blue color-conversion material **30**B that emits blue light **52**. In an embodiment, the micro-LEDs **40** emit light **50** having a frequency higher than the frequency of light **52** emitted by the color-conversion material **30**. The micro-LEDs **40** can all emit the same frequency of light **50** and can be solid-state micro-LED lasers. The color conversion structures **10** can include light-scattering or light-diffusive elements. In one embodiment of the display **62**, the display substrate **22** is between the micro-LEDs **40** and the color-conversion structures **10**. In another embodiment, the color-conversion structures **10** are between the micro-LEDs **40** and the display substrate **22**.

In all of the display embodiments of the present invention, the micro-LEDs **40** or (micro-LED lasers) of a pixel group can be located in a row, as shown in the Figures, or in a two-dimensional arrangement, for example forming a triangle on the display substrate **22** surface (not shown).

In an embodiment of the present invention, the display **62** or micro-LED laser display **64** is a backlight unit (BLU). Control of the individual micro-LEDs **40** can enable local dimming, for example in a liquid crystal display.

Referring to FIG. **15**, in a method of the present invention, a source wafer is provided in step **100** and one or more micro-LEDs **40** are formed on the source wafer in step **110** in a micro-transfer printable configuration, for example with an underlying release portion or sacrificial portion **18**. The source wafer can be a semiconductor wafer. In step **120**, a source substrate **20** distinct from the source wafer, for example made of glass, is provided and one or more corresponding color-conversion layers **34** are formed on the source substrate **20** in step **130**, for example with an underlying release portion or sacrificial portion **18**. The micro-LEDs **40** are released, for example by etching the sacrificial portions **18** before micro-transfer printing the micro-LEDs **40**. In step **140**, the micro-transfer printable micro-LEDs **40** are micro-transfer printed onto the corresponding color-conversion layers **34** to form a pixel structure **60**. Additional adhesive layers, for example, curable resins can be provided and cured to adhere the micro-LEDs **40** to the color-conversion layers **34** (not shown). The sacrificial portions **18** beneath the color-conversion layers **34** are then etched or otherwise removed in step **150** to release the color-conversion layer **34** and form the pixel structures **60** of FIG. **6**. In step **160**, the pixel structures **60** are micro-transfer printed to a destination substrate **22**. An array of the pixel structures **60** can be micro-transfer printed to the destination substrate **22** to form the display **62**.

In an alternative embodiment of the present invention referring to FIG. **16**, the color-conversion layers **34** are released and micro-transfer printed onto the corresponding micro-LEDs **40** in step **141** in place of step **140** to form the pixel structures **60** as illustrated in FIG. **7** (with the addition of the first layer **36** as shown in FIGS. **4** and **5**). In either of the embodiments of FIGS. **15** and **16**, the color conversion layers **34** of FIGS. **1** and **3** can be used in place of the color-conversion layers **34** illustrated in FIG. **4**.

Referring to FIG. **17**, in another method of the present invention, a source wafer is provided in step **100** and one or more micro-LEDs **40** are formed on the source wafer in step **110** in a micro-transfer printable configuration, for example with an underlying release or sacrificial portion **18**. The source wafer can be a semiconductor wafer. In step **120** a source substrate **20** distinct from the source wafer, for example made of glass, is provided and one or more corresponding color-conversion layers **34** are formed on the source substrate **20** in step **130**, for example with an underlying release or sacrificial portion **18**. The sacrificial portions **18** of the source wafer are removed to release the micro-LEDs **40** from the source wafer in step **151**. The sacrificial portions **18** of the source substrate **20** are removed to release the color-conversion layers **34** from the source substrates **20** in step **152**. In step **170**, the micro-transfer printable micro-LEDs **40** are micro-transfer printed onto the destination substrate **22**. In step **180**, the color-conversion layers **34** are correspondingly micro-transfer printed onto the micro-LEDs **40** to form the pixel structures **60** of FIG. **8**. Additional adhesive layers, for example curable resins, can be provided and cured to adhere the micro-LEDs **40** to the color-conversion layers **34** (not shown). An array of the micro-LEDs **40** and corresponding color-conversion layers **34** can be micro-transfer printed to the destination substrate **22** to form the display **62**.

In an alternative embodiment of the present invention and referring to FIG. **18**, the color-conversion layers **34** are micro-transfer printed onto the destination substrate **22** in step **171** in place of step **170**. The micro-LEDs **40** are then micro-transfer printed onto the corresponding color-conversion layer **34** in step **181** in place of step **180** to form the pixel structures **60** of FIG. **9**. In either of the embodiments of FIGS. **23** and **24**, the color conversion layer **34** of FIGS. **1** and **3** can be used in place of the color-conversion layer **34** illustrated in FIGS. **8** and **9**.

In yet another embodiment of the present invention referring to FIG. **19**, a source wafer is provided in step **100** and one or more micro-LEDs **40** are formed on the source wafer in step **110** in a micro-transfer printable configuration, for example with an underlying release or sacrificial portion **18**. The source wafer can be a semiconductor wafer. The micro-LEDs **40** are printed on the destination substrate **22** in step **170**. In step **120** a source substrate **20** distinct from the source wafer, for example made of glass, is provided and one or more corresponding color-conversion layers **34** are formed on the source substrate **20** in step **130**, for example with an underlying release or sacrificial portion **18**. The color-conversion layers **34** are printed on the destination substrate **22** in step **171**, for example on a side of the display substrate **22** opposite the side of the display substrate **22** on which the micro-LEDs **40** are disposed. The color-conversion layers **34** are printed in spatial correspondence with the micro-LEDs **40** so the light **50** emitted from the micro-LEDs **40** propagates into the color-conversion layers **34**, as shown in FIG. **10**. Steps **170** and **171** can be performed independently, at different times, or in different places. In various embodiments, the color-conversion layers **34** are micro-transfer printed or, especially with reference to FIG. **11**, screen printed or otherwise photolithographically formed.

In all of these embodiments, the reflective structures **44** or light-diffusive layers **54** or **56**, or encapsulation layer **16** can be formed and patterned as necessary using photolithographic or lamination processes.

In various methods of the present invention, the pixel structures **60**, micro-LEDs **40**, or color-conversion layers **34** are micro-transfer printed to a display substrate **22**. For a discussion of micro-transfer printing techniques see, U.S. Pat. Nos. 8,722,458, 7,622,367 and 8,506,867, each of which is hereby incorporated by reference.

In another method of the present invention, the pixel structures **60** are disposed on the display substrate **22** by micro-transfer printing using compound micro assembly structures and methods, for example as described in U.S. patent application Ser. No. 14/822,868, filed Aug. 10, 2015, entitled Compound Micro-Assembly Strategies and Devices, which is hereby incorporated by reference in its entirety. The micro-LED **40** structures on the display substrate **22** can be interconnected using photolithographic methods or using printed circuit board methods and materials, for example to a display controller (not shown).

In useful embodiments, the display substrate **22** includes material, for example glass or plastic, different from a material in an integrated-circuit or chiplet substrate, for example a semiconductor material such as silicon. The display substrate **22** usefully has two opposing smooth sides suitable for material deposition, photolithographic processing, or micro-transfer printing of color-conversion structures **10**. The display substrate **22** can have the size of a conventional display, for example a rectangle with a diagonal of a few centimeters to one or more meters. Such substrates are commercially available. The display substrate **22** can include polymer, plastic, resin, polyimide, PEN, PET, metal, metal foil, glass, a semiconductor, or sapphire and have a transparency greater than or equal to 50%, 80%, 90%, or 95% for visible light. In some embodiments of the present invention, the color-conversion structures **10** emit light **52** through the display substrate **22**. In other embodiments, the color-conversion structures **10** emit light **52** in a direction opposite the display substrate **22**. The display substrate **22** can have a thickness from 5 to microns, 10 to 50 microns, 50 to 100 microns, 100 to 200 microns, 200 to 500 microns, 500 microns to 0.5 mm, 0.5 to 1 mm, 1 mm to 5 mm, 5 mm to 10 mm, or 10 mm to 20 mm. According to embodiments of the present invention, the display substrate **22** can include layers formed on an underlying structure or substrate, for example a rigid or flexible glass or plastic substrate.

According to various embodiments, the micro-transfer-printed displays **62**, **64** of the present invention include a variety of designs having a variety of resolutions, color-conversion structure **10** sizes, and displays having a range of display areas. For example, display areas ranging from 1 cm by 1 cm to 10 m by 10 m in size are contemplated. The resolution of color-conversion structures **10** over a display area can also vary, for example from tens of color-conversion structures **10** per inch to hundreds of color-conversion structures **10** per inch. Thus, the present invention has application in both low-resolution and very high-resolution displays and from very small to very large displays.

In an embodiment, the micro-LEDs **40** are formed in substrates or on supports separate from the display substrate **22**. For example, the color-conversion structures **10**, micro-LEDs **40** are separately formed in a semiconductor source wafer. The color-conversion structures **10** micro-LEDs **40** are then removed from the source wafer and transferred, for example using micro-transfer printing, to the display substrate **22** or to a compound micro-assembly substrate (not shown).

By employing a multi-step transfer or assembly process, intermediate testing is enabled, increased yields are achieved, and costs are reduced for the micro-transfer-printed displays **62**, **64** of the present invention. Additional details useful in understanding and performing aspects of the present invention are described in U.S. patent application Ser. No. 14/743,981, filed Jun. 18, 2015, entitled Micro Assembled LED Displays and Lighting Elements, which is hereby incorporated by reference in its entirety.

As is understood by those skilled in the art, the terms “over”, “under”, “above”, “below”, “beneath”, and “on” are relative terms and can be interchanged in reference to different orientations of the layers, elements, and substrates included in the present invention. For example, a first layer on a second layer, in some embodiments means a first layer directly on and in contact with a second layer. In other embodiments, a first layer on a second layer can include another layer there between. Additionally, “on” can mean “on” or “in.” As additional non-limiting examples, a sacrificial layer or sacrificial portion **18** is considered “on” a substrate when a layer of sacrificial material or sacrificial portion **18** is on top of the substrate, when a portion of the substrate itself is the sacrificial layer, or when the sacrificial layer or sacrificial portion **18** comprises material on top of the substrate and a portion of the substrate itself.

Having described certain embodiments, it will now become apparent to one of skill in the art that other embodiments incorporating the concepts of the disclosure may be used. Therefore, the invention should not be limited to the described embodiments, but rather should be limited only by the spirit and scope of the following claims.

Throughout the description, where apparatus and systems are described as having, including, or comprising specific components, or where processes and methods are described as having, including, or comprising specific steps, it is contemplated that, additionally, there are apparatus, and systems of the disclosed technology that consist essentially of, or consist of, the recited components, and that there are processes and methods according to the disclosed technology that consist essentially of, or consist of, the recited processing steps.

It should be understood that the order of steps or order for performing certain action is immaterial so long as the disclosed technology remains operable. Moreover, two or more steps or actions in some circumstances can be conducted simultaneously. The invention has been described in detail with particular reference to certain embodiments thereof, but it will be understood that variations and modifications can be effected within the spirit and scope of the invention.

PARTS LIST

10 color-conversion structure
12 tether
14 anchor
16 encapsulation layer
18 sacrificial portion
20 substrate/source substrate/source wafer
22 destination substrate/display substrate/transparent substrate
30 color-conversion material
30R red color-conversion material that emits red light
30G green color-conversion material that emits green light
30B blue color-conversion material that emits blue light
32 transparent matrix
34 color-conversion layer
35 article
35R red color-conversion article
35G green color-conversion article
35B blue color-conversion article
36 first layer
38 second layer
40 micro light-emitting diode (micro-LED)
42 dielectric layer
43 micro-LED light-emitting side
44 reflective structure/layer
45 light absorbers
46 first electrode
48 second electrode
50 light emitted from micro-LED
52 light emitted from color-conversion material
53 diffuse light
54 light diffuser
55 diffusive reflector
56 light-diffusive layer/light diffuser
57 refractive lens
58 light-diffusive particle
60 pixel structure
62 display
64 micro-LED laser display
100 provide source wafer step
110 form micro-LED on wafer step
120 provide source substrate step
130 form color-conversion layer on wafer step
140 micro-transfer print micro-LED on color-conversion layer step
141 micro-transfer print color-conversion layer on micro-LED step
150 release pixel structure step
151 release micro-LEDs step
152 release color-conversion layers step
160 micro-transfer print pixel structure on destination substrate step
170 micro-transfer print micro-LED on destination substrate step
171 micro-transfer print color-conversion layer on destination substrate step
180 micro-transfer print color-conversion layer on micro-LED step
181 micro-transfer print micro-LED on color-conversion layer step

What is claimed is:

1. A color-conversion structure, comprising:

an article comprising a color-conversion material disposed within a color-conversion layer, wherein the color-conversion material re-emits or redirects light by absorbing electromagnetic radiation of a relatively higher frequency and emitting electromagnetic radiation of a relatively lower frequency;

at least a portion of a tether connected to the article, wherein the at least a portion of a tether extends from the article.

2. The structure of claim **1**, wherein the article comprises:

a first layer;

the color-conversion material disposed on and in contact with the first layer; and

a second layer disposed on and in contact with the color-conversion material, the first and second layers encapsulating the color-conversion material.

3. The structure of claim **1**, comprising a micro-light-emitting diode (micro-LED) having a light-emitting side disposed to emit light toward the color-conversion material.

4. The structure of claim **3**, wherein the micro-LED is a solid-state laser.

5. The structure of claim **1**, comprising:

a source substrate having one or more sacrificial portions;

the color-conversion layer disposed on or over each of the sacrificial portions; and

the tether extending from a periphery of the sacrificial portion.

6. The structure of claim **5**, comprising a micro-light-emitting diode (micro-LED) having a light-emitting side disposed to emit light toward the color-conversion material and wherein the color-conversion material is located between the micro-LED and the sacrificial layer.

7. The structure of claim **5**, comprising a micro-light-emitting diode (micro-LED) having a light-emitting side disposed to emit light toward the color-conversion material and wherein the micro-LED is located between the color-conversion material and the sacrificial layer.

8. The structure of claim **1**, comprising a micro-light-emitting diode (micro-LED) having a light-emitting side disposed to emit light toward the color-conversion material and, optionally wherein the micro-LED is a micro-transfer printable or micro-transfer printed micro-LED, forming a pixel structure.

9. The structure of claim **8**, comprising a transparent destination substrate and wherein the pixel structure is disposed on the transparent destination substrate.

10. The structure of claim **8**, comprising a destination substrate and wherein the pixel structure is disposed on the destination substrate and the color-conversion material is located between the micro-LED and the destination substrate or the pixel structure is disposed on the destination substrate and the destination substrate is located between the micro-LED and the color-conversion material.

11. The structure of claim **8**, comprising a destination substrate and wherein the pixel structure is disposed on the destination substrate and the micro-LED is located between the color-conversion material and the destination substrate.

12. A color-conversion structure, comprising:

a source substrate having one or more sacrificial portions; and

one or more pixel or sub-pixel structures, each pixel or sub-pixel structure comprising:

an article comprising a color-conversion material that re-emits or redirects light by absorbing electromagnetic radiation of a relatively higher frequency and emitting electromagnetic radiation of a relatively lower frequency disposed within a color-conversion layer on or over each of the sacrificial portions,

a micro-light-emitting diode (micro-LED) having a light-emitting side disposed to emit light toward the color-conversion material, the article disposed on the micro-LED on a side of the micro-LED opposite the sacrificial portion, and

one or more tethers, each tether extending from the micro-LED.

13. The structure of claim **12**, wherein the micro-LED is an organic or inorganic solid-state laser or an organic or inorganic semiconductor laser.

14. A display, comprising:

a display substrate;

an array of color-conversion structures disposed on the display substrate, each color-conversion structure comprising a micro-light-emitting diode (micro-LED) disposed to emit light toward an article comprising a color-conversion material on the display substrate, wherein the color-conversion material re-emits or redirects light by absorbing electromagnetic radiation of a relatively higher frequency and emitting electromagnetic radiation of a relatively lower frequency; and

at least a portion of a tether extending from the article.

15. The display of claim **14**, wherein the micro-LEDs are lasers.

16. The display of claim **14**, wherein each micro-LED has an anode and a cathode disposed on a same side of the respective micro-LED and, optionally, the anode and cathode of a respective light emitter are horizontally separated by a horizontal distance, wherein the horizontal distance is from 100 nm to 500 nm, 500 nm to 1 micron, 1 micron to 20 microns, 20 microns to 50 microns, or 50 microns to 100 microns.

17. A display, comprising:

a display substrate;

an array of color-conversion structures disposed on the display substrate, each color-conversion structure including a micro-light-emitting diode (micro-LED) disposed to emit light toward an article comprising a color-conversion material on the display substrate, wherein the display substrate is between the article and the micro-LED and the color-conversion material re-emits or redirects light by absorbing electromagnetic radiation of a relatively higher frequency and emitting electromagnetic radiation of a relatively lower frequency.

18. The display of claim **17**, wherein the micro-LEDs are lasers.

19. A method of making a display, comprising:

providing a source wafer and a source substrate;

forming a plurality of micro-LEDs on the source wafer and a corresponding plurality of color-conversion structures on the source substrate, wherein the color-conversion structures each comprise a color-conversion material that re-emits or redirect lights by absorbing electromagnetic radiation of a relatively higher frequency and emitting electromagnetic radiation of a relatively lower frequency;

micro-transfer printing the micro-LEDs onto the color-conversion structures to form a plurality of respective pixel structures or micro-transfer printing the color-conversion structures onto the micro-LEDs to form a plurality of respective pixel structures; and

micro-transfer printing the plurality of pixel structures onto a destination substrate to form the display.

20. A method of making a display, comprising:

providing a source wafer and a source substrate;

forming a plurality of micro-LEDs on the source wafer and a corresponding plurality of color-conversion structures on the source substrate, wherein the color-conversion structures each comprise a color-conversion material that re-emits or redirect lights by absorbing electromagnetic radiation of a relatively higher frequency and emitting electromagnetic radiation of a relatively lower frequency; and

micro-transfer printing the micro-LEDs onto a destination substrate and micro-transfer printing the color-conversion structures onto respective micro-LEDs or micro-transfer printing the color-conversion structure onto a destination substrate and micro-transfer printing micro-LEDs onto respective color-conversion structures to form a plurality of respective pixel structures forming the display.

21. A method of making a display, comprising:

providing a source wafer and a source substrate;

forming a plurality of micro-LEDs on the source wafer and a corresponding plurality of color-conversion structures on the source substrate, wherein the color-conversion structures each comprise a color-conversion material that re-emits or redirect lights by absorbing electromagnetic radiation of a relatively higher frequency and emitting electromagnetic radiation of a relatively lower frequency; and

micro-transfer printing the micro-LEDs onto a first side of a destination substrate and micro-transfer printing color-conversion structures onto a second side of the destination substrate opposite the first side and in correspondence with the micro-LED to form an array of pixels in the display.

* * * * *

专利名称(译)	色彩转换显示		
公开(公告)号	US10431719	公开(公告)日	2019-10-01
申请号	US14/930363	申请日	2015-11-02
[标]申请(专利权)人(译)	艾克斯瑟乐普林特有限公司		
申请(专利权)人(译)	的X CELEPRINT有限公司		
当前申请(专利权)人(译)	的X CELEPRINT有限公司		
[标]发明人	COK RONALD S BOWER CHRISTOPHER MEITL MATTHEW		
发明人	COK, RONALD S. BOWER, CHRISTOPHER MEITL, MATTHEW		
IPC分类号	H01L21/00 H01L23/482 H01L23/538 H01L25/075 H01L33/62 H01L33/50 H01L33/60 H05B33/08 G02B26/04 G02F1/167 H01L25/16 H01L33/36 H01L33/48 H05K1/03 H05K1/09 H05K1/18 H05K5/00 G09G3/22 H01L27/15 F21V9/08 H01L33/58 G09G3/32 H01L33/38 F21K9/60 H01L33/40 H01L33/20 F21Y101/00 F21Y105/00 F21Y105/10 F21Y113/13 F21Y115/10		
CPC分类号	H05K1/181 H01L25/167 H01L33/502 H01L33/508 H01L33/62 H05B33/089 H01L33/48 H05K1/0306 H01L25/0753 H01L27/156 H01L33/38 G09G3/32 F21K9/60 H01L23/4821 H01L33/36 H05K1/182 H01L33/60 F21V9/08 G02F1/167 G09G3/22 H01L33/58 G02B26/04 H01L33/385 H01L23/5381 H05K1/09 H05K5/0017 H01L33/50 F21Y2113/13 H05K2201/10106 H05K2201/10166 F21Y2105/00 G09G2300/0842 H05K2201/10128 F21Y2115/10 G09G2310/0264 H01L33/20 F21Y2101/00 F21Y2105/10 H01L33/405 H01L2224/73267 G09G2300/0452 H01L2224/18 H01L2224/92244 H05K2201/0329 H05B45/50		
代理人(译)	施米特MICHAEL D.		
其他公开文献	US20170122502A1		
外部链接	Espacenet		

摘要(译)

颜色转换结构包括制品，该制品包括设置在颜色转换层内的颜色转换材料。系绳的至少一部分在制品内或从制品延伸。可以将颜色转换结构设置在基板的牺牲部分上以形成可微转印的可印刷装置，并将其微转印到显示基板上。颜色转换结构可以包括在物品上方或下方的发光二极管或激光二极管。或者，该制品位于显示基板的与无机发光二极管相对的一侧。显示器包括设置在显示基板上的颜色转换结构的阵列。