A Field Emission Light Source Using a Reticulated Vitreous Carbon (RVC) Cathode and Cathodoluminescent Phosphors

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***Abstract*—A field emission light source using cathodoluminescent (CL) phosphors and a reticulated vitreous carbon (RVC) cathode is presented. The flat-format design requires no microfabrication technology and can be easily configured for light emission at different wavelengths, ranging from UV to visible, to infrared. The operation of a visible-spectrum light source was demonstrated by testing both unpackaged devices in a vacuum environment and proof-of-concept packaged lamps. The results exhibited excellent field emission properties with a minimum extraction field of 1.7 V/μm and good uniformity. Luminance characteristics were also excellent, with a white CL phosphor being excited up to approximately 12 000 Cd/m^2. Lower levels of luminance are applicable to display backlights.**

***Index Terms*—Carbon, vacuum microelectronics, cathodoluminescence (CL), electron sources, light sources, phosphors.**

I. INTRODUCTION

SPECIALTY light source technologies, now being used to achieve energy-efficient lighting, each have particular limitations. Conventional incandescent, although providing excellent appearance, is inefficient. Fluorescent lamps are limited by their size (with respect to luminous flux), toxicity (containing mercury) and problems with temperature-sensitive ballasts (power supplies). Semiconductor light emitting diodes (“white LEDs”), due to the nature of their operation, are problematic due to droop [1] and also due to major thermal dissipation problems [2]. Furthermore, cost and manufacturing issues can restrict particular lamp types to a narrow range of applications; therefore, there is need for new lighting technologies to complement existing ones.

This presentation demonstrates a type of field emission lamp (the “FE-lamp”). It is a robust and low-cost light source using a field emission electron source and cathodoluminescent (CL) phosphors. Field emission electron sources are low-power, temperature-insensitive, and unaffected by radiation [3]. Additionally, using different cathodoluminescent phosphors enables light emission at different wavelengths without major changes in device design. With these goals in mind, a practical design was engineered that required no microfabrication technology. The viability of the design is demonstrated, first using a vacuum chamber fixture and then, also within a proof of concept standalone vacuum package.

This light source has flexibility, affording many potential applications. Visible-spectrum lamps are useful in conventional general lighting, large-area displays, as well as in specialty lamps. The flat-format design presented can be configured to emphasize high brightness, high energy efficiency, specific spectral content, long lifetime, specific form factor, or low cost. Lower luminance levels (such as $\leq$ 1200 Cd/m^2) and a high color temperature (for example, 15 000 K) would make this lamp particularly suitable as a backlight for flat LCD displays. There have been other field-emission lamps designed and demonstrated [4]–[7], however these use different types of cathodes, and cannot be readily adapted to the flat format (“light tile”) which we examine and demonstrate here. They also use other types of cathodes which have limitations not associated with the reticulated vitreous carbon (RVC) cathode we employ (described below.) Field-emission lamps (FE-lamps) can also be configured with CL phosphors that emit in the visible spectrum with varying color temperature or even in the ultraviolet or infrared range. This technique can potentially be employed for light sources in miniature gas sensors or operated as a pump source for lasers, optical switches, and amplifiers. Because field emission devices operate in a vacuum environment, FE-lamps are naturally suitable for use in outer space, such as illumination sources for cameras or for ultraviolet (UV) or infrared (IR) spectrometers.

II. STRUCTURE OF FIELD EMISSION LIGHT SOURCE

The field emission light source combines the versatility of CL phosphors, which have been used for high color quality in cathode ray tubes (CRT) for years, with the advantages of field emission to produce a robust light-generating source of high luminance, low power, and low manufacturing cost. The conceptual structure of the device is presented in Fig. 1 from a cross-sectional point of view. It is readily seen that this lamp operates as a vacuum diode, although, in principle, triode and higher configurations are possible.

The glass face plate and the glass base plate serve as the main substrates and supporting structures for the field emission light

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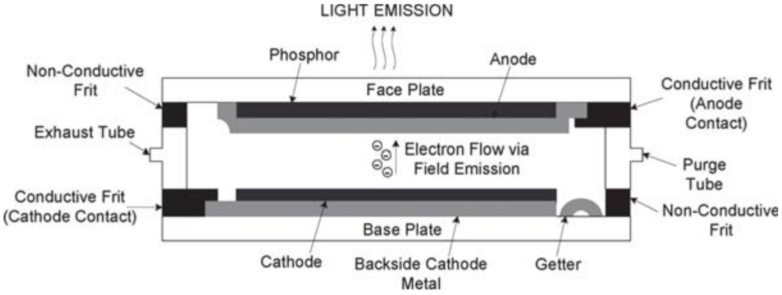


Fig. 1. Cross-sectional conceptual schematic of the field emission light source. The outer package components (face plate, base plate, sidewalls and tubulation) are all made of glass.

source. The face plate acts as the substrate for the CL phosphor and anode material. It must be of a material suitable for the transmission of light emitted from the respective phosphor; for example, for a visible-spectrum light source (380–740 nm), borosilicate glass can be used. The base plate serves as the substrate for the field emission cathode. It should be of the same material as the face plate to ensure matching coefficients of thermal expansion; this prevents structural damage during the high-temperature assembly steps. Layers of CL phosphor, cathode material, or anode material are subsequently joined to the respective plates through screen printing, electron beam evaporation, or manual attachment. Sidewalls, made of the same material as the substrates, connect the face plate and base plate together; they also help maintain a constant spacing between the anode and the cathode. In the demonstration package we built, the sidewalls are attached to the face plate and base plate via frit seals. The anode-cathode spacing is the critical dimension for determining the onset of field emission, since the electron extraction is resultant of the parallel-plate field between the anode and cathode surfaces.

Most field emission cathodes used for vacuum microelectronics have always been based on variations of the metal or Si microtips pioneered by Spindt [8]. However, fabrication of the Spindt tip field emitter calls for multiple lithographic steps. This complexity makes them impractical for applications requiring large-area emission, such as FE-lamps. Recently, large-area cathodes based on carbon nanotubes or surface treatment of printed graphite paste have been demonstrated to be viable field emitters [9]–[11]. The FE-lamp demonstrated utilizes RVC, a porous, glassy carbon as the field emission cathode. RVC is easy to shape, either by molding or machining, and has excellent electrical properties, as the field emission cathode [12]. It has been shown that surface treatment of RVC using Argon ion irradiation can produce random nanostructures on the surface that are also excellent for field emission [13]. This surface modification process is similar to what has been demonstrated with printed graphite paste [10], [14]. The cathode is bonded to the base plate substrate using a commercial conductive silver composition. Results have shown that this material is capable of producing uniform, high current emission for long periods of time ($\geq$10 000 hours) in part due to the self-assembly process during operation as a cathode [15].

For the anode material, metals with high reflectivity, such as aluminum, are preferable. The anode material is applied on top of the CL phosphor as depicted in Fig. 1. Since the phosphor emits light in both the forward and backward directions, the high reflectivity of the aluminum is advantageous because light emitted toward the cathode will be reflected through the face plate. This method, similar to aluminization technology used for CRT pixels [16], enables emission of the majority of the light produced by the phosphor.

The FE-lamp also consists of several other important components. The CL phosphor, stimulated by the electrons emitted from the cathode, is the source of the luminescence. A variety of CL phosphors exist [17] and can be selected to produce light emission at different wavelengths. It has also been shown that high-efficacy in white light sources can be obtained using CL phosphors, with significant flexibility of color temperature and spectral content [18]. The vacuum getter, composed of a reactive metal such as barium, maintains the vacuum environment once the interior of the light source has been evacuated and sealed. Any residual gases or desorbed materials are prevented from remaining in a free state by the getter. Additionally, frit, made from a finely crushed form of the substrate material, is used to seal the device. Conductive frit—frit infused with powdered metal such as Ag or Au (10% by weight)—is selectively patterned (we use thick-film screen printing) to provide electrical leads to the interior as seen in Fig. 1. Also, "purge" and "exhaust" tubes on the sidewalls of the device aid in the vacuum evacuation of the lamp interior during packaging.

III. VACUUM CHAMBER PRELIMINARY EVALUATION OF THE FIELD EMISSION LIGHT SOURCE

In order to evaluate the lamp operation over a range of anode–cathode spacing values as well as with different phosphors, as well as to estimate optimum operational parameters, testing was performed on anodes and cathodes fixtured in a vacuum chamber using a configuration analogous to the lamp concept of Fig. 1. Data is presented here from a visible-spectrum CL phosphor and a RVC cathode fixtured in the vacuum chamber; it does not contain a getter or any packaging sidewall components. The vacuum chamber configuration shown here also utilized indium tin oxide (ITO), a transparent conductive coating, for the anode material, rather than a reflective metal, due to the lower cost, simplicity, and greater flexibility during the (phosphor) evaluation process. A comparison between using a metal (like Al) and a conductive coating (like ITO) as the anode is presented in Fig. 2. The phosphor in this case was deposited on top of the anode coating. The anode configuration differs somewhat from the aluminized method we used in the packaged device; however, this was not critical to the evaluation process in demonstrating the "proof of principle" operation of

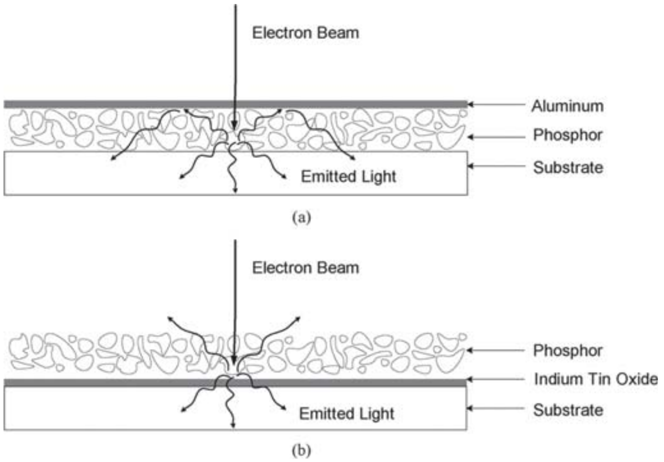


Fig. 2. Comparison of light emission between devices with (a) aluminum and (b) ITO anodes. Adapted from [16]. (Used with permission from K. Y. Sasaki, J. B. Talbot, and Wiley-VCH).

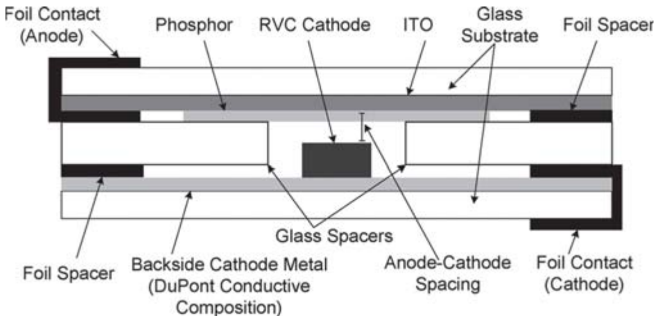


Fig. 3. Cathodoluminescent phosphor field emission light source for vacuum chamber testing.

the field emission light Current-voltage (*I-V*) and luminance characteristics were measured for the vacuum chamber configuration. The anode-cathode spacing for the data shown was 2 mm and vacuum levels were maintained at lower than 2×10^{-6} Torr using a turbomolecular pump. An example semilog *I-V* curve is shown in Fig. 4(a). The minimum extraction field, defined as the applied field where the current reached 0.1 μA, in this case was measured to be 1.7 V/μm. The linear behavior observed in the Fowler-Nordheim curve in Fig. 4(b) confirms electron extraction through field emission.

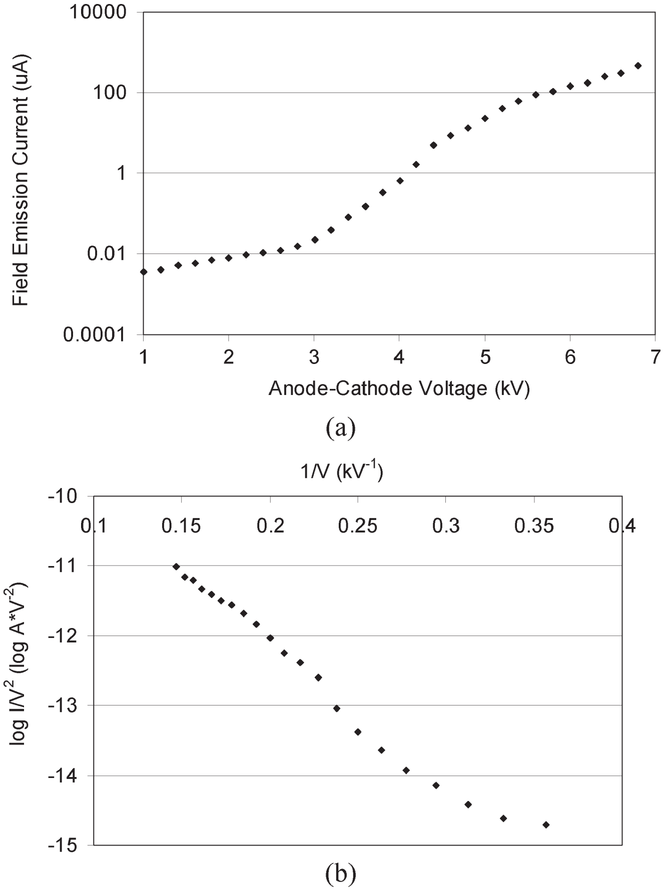


Fig. 4. (a) *I-V* characteristics for field emission light source tested in vacuum chamber. The anode-cathode spacing in this case was 2 mm. (b) Fowler-Nordheim curve for field emission light source tested in vacuum chamber. The anode-cathode spacing was 2 mm.

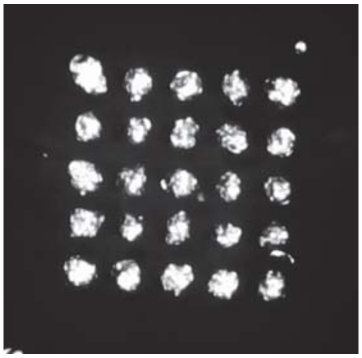
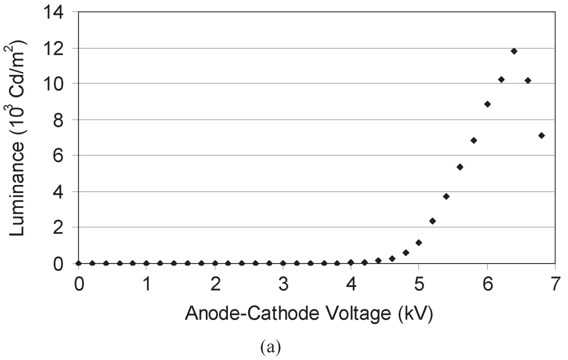


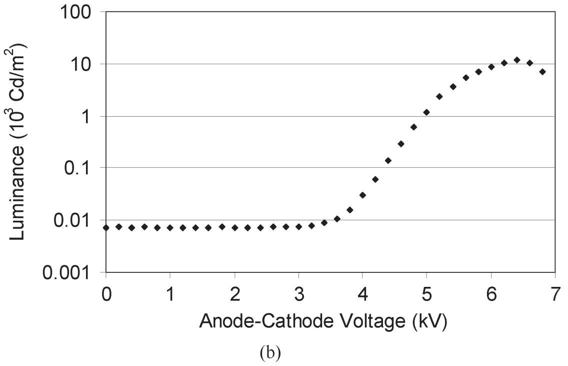
Fig. 5. Photo of illuminated field emission light source in vacuum chamber. (Surface-treated with shadow mask of 5 by 5 array of 0.5 mm-diameter dots spaced 1 mm apart.).

A photo of the illuminated phosphor, at low brightness, is shown in Fig. 5. The light areas seen in the figure show light emission due to stimulation of the phosphor by electrons emitted from patterned dot regions of the cathode which were selectively treated by the Argon ion irradiation [13]. The purpose of this patterning was first to clarify how well the emission could be isolated to the regions which had received Ar^+ ion irradiation. Secondly, we wished to evaluate the extent of blooming in the phosphor screen, in order to design packaged devices for optimum uniformity of emission. The figure makes it clear that strong field emission from the RVC is constrained to the irradiated areas, which were shadow-masked from the Argon ion beam during surface treatment, as expected. In a packaged device, the lateral spacing between the individual openings in the shadow mask would be decreased, resulting in this "dot" pattern not being seen in the illumination across the entire anode area. It is clear that the emission uniformity, even at the limited level of emission as shown, is quite good, with little emission outside the surface-treated areas.

Luminance characteristics, measured using a calibrated Konica-Minolta LS110 luminance meter, for a 2 mm spacing are presented in Fig. 6. We did not measure above 7 kV at 2 mm spacing due to the danger of arc discharge. In a commercial device, superior efficacy would be obtained at higher voltages (such as 15 kV, where x-ray emission is still negligible [18].) As



(a)



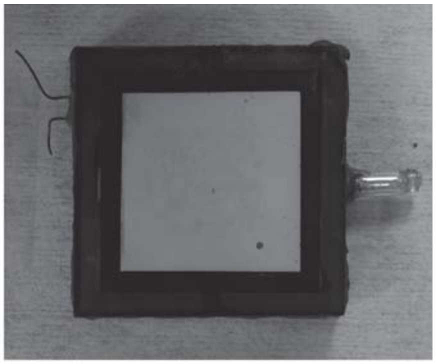
(b)

Fig. 6. Luminance characteristics for field emission light source tested in vacuum chamber. The anode-cathode spacing was 2 mm.

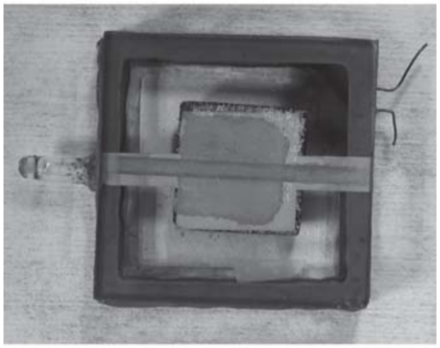
anticipated, it was observed that above the minimum field emission extraction voltage, the luminance increases with increasing applied anode-cathode voltage. At an applied voltage of 6.4 kV, the luminance of the light source reaches a peak of 11830 Cd/m^2, approximately four times the measured luminance of a typical fluorescent light. A practical packaged field emission light source with an aluminum cathode can be expected to have a luminance up to twice this value. We believe the decrease in the luminance at anode-cathode voltages above 6.4 kV is due to thermal heating of the phosphor-ITO combination. The measurement entirely in vacuum (without the convective heat dissipation which lamps have in room ambient) is not able to have optimal thermal dissipation performance, and therefore the loss of efficacy at higher power densities is as expected [18]. We anticipate that optimized package design would eliminate these losses. A pulsed power supply, rather than the DC supply used, would also mitigate this.

IV. FABRICATION OF A FIELD EMISSION LIGHT SOURCE

As a result of our vacuum-system preliminary analyses, we constructed packaged devices, using the concept depicted in Fig. 1. The fabrication of the FE-lamp is as follows. The substrate glass for the face plate and base plate is cut to 2 inch square size and cleaned using standard cleaning solutions. All flat glass components are ordinary 2.5 mm thick boro-silicate. The purge tubing is 1/8 inch OD boro-silicate. They are lightly etched in mild hydrofluoric acid to promote the adherence of subsequent layers. For the base plate, the RVC is shaped to 1 inch, square, and attached using the conductive composition. The RVC is then treated with Argon ion irradiation to optimize the cathode surface for field emission. A shadow mask is used to limit ion irradiation to only the areas of the RVC where strong field emission is desired. Spreading the points of field emission apart also assures the cathode will operate with a uniform current density. The face plate is coated with the CL phosphor by using a silk screen-printing process. Lacquer is applied to give the phosphor a specular surface. The anode Al (700 Å) is deposited on top of the lacquered phosphor by electron beam evaporation. The face plate is baked in air at 425° C to char the lacquer and to sinter the reflective Al. The Al oxidizes slightly (estimated to be about 20 Å), but this is acceptable. This sequence of phosphor screening steps is similar to those commonly used in the CRT display industry [16]. The "purge" and "exhaust" tube is welded to the sidewalls. Once the frit bonds the sidewalls, face plate, and base plate together, nitrogen is introduced into the interior of the lamp package. The 1/8 inch purge/exhaust tube provides an inlet/outlet, for nitrogen before sealing. A high-temperature bake is performed during the purge and exhausting to force outgassing from the interior package surfaces. Upon completion of this cycle, the entire package is evacuated and sealed. Finally, the getter (in this case, an active getter, whose wires are seen clearly in Fig. 7) is activated by resistive heating. The device, in the diode configuration, is operated with the application of a positive anode to cathode voltage through the exterior points of the conductive frit, as shown in Fig. 1. A photo of a functional "proof of principle" FE-lamp is shown in Fig. 7.



(a)



(b)

Fig. 7. A packaged FE-lamp. (a) A view from the face plate side. (b) A view from the base plate side.

The FE-lamp of Fig. 7 was tested to verify operation up to 10 kV-DC, which was the limit of our external power supply. Four experimental devices were made, and two were functional. Significant field emission current and light emission was observed. The anode-cathode spacing in this demonstration is a fixed 4 mm value. The efficacy of the phosphor in the packaged devices exceeds 45 lm/W (about 3× the efficacy of a standard 100 W incandescent lightbulb), which is in agreement with earlier experiments [18]. This value does not include the power-supply and system efficiencies, which in a commercial device would need to be optimized.

The current–density voltage relationship in the packaged device matched the expectations which could be extrapolated (given the differing area) from Fig. 5, however, no lamp output was observed until approximately 4 kV applied voltage. This is due to the energy drop associated with the transmission of electrons through the thin Al layer covering the phosphor (in contrast to the bare phosphor on ITO from which the data of Fig. 7 was measured.)

Although the packaged parts functioned up to 10 kV, stable measurement of current and luminance (at values above 200 Cd/m^2) was not possible due to sporadic arcs inside the package at higher voltages. We believe this is due to residues from the frit-seal process, or other particulates liberated inside the package during the fabrication of the device. One or more of the seals (pinch tube, frits, metal–glass getter feedthroughs) also slowly failed; therefore, the device lifetime of these (hand-made) was limited to a few hundred hours.

A. Discussion

Although the packaged devices made were satisfactory in proving the FE-lamp concept in this configuration, there are several important observations, applicable to commercial devices. First, it is clear that molded-glass packages with minimal frit seals would be less complex and more reliable (although not practical in our experiments.) Since glass is a heavy commodity, it would likely be preferred to use arched surfaces where possible (rather than flat, such as we used) in order to minimize the quantity of glass used and to strengthen the package under vacuum. Also, since this flat configuration is extendable to vitually any desired size, it is likely that spacers or standoffs (such as used in field-emission displays) would be required for larger formats. Furthermore, especially in larger formats, passive gettering techniques, which are less expensive (such as flash getters), would be preferred. Also, in our experiment we used a diode field emitter; however, is possible that a triode configuration, which has been demonstrated as being feasible for large-area emission [15], might (in some cases) be preferred. Finally, it is clear that the simplistic dc high-voltage 10 kV external power supply we employed is not optimum for either efficiency or cost (in a consumer product): both higher voltages and pulse excitation of the phosphors would likely be an improvement [19].

V. CONCLUSION

A field emission light source using a RVC cathode and CL phosphors has been conceptually designed, studied and demonstrated in a proof-of-concept device. The general structure and assembly process for the device is presented. Testing of both a packaged and an unpackaged field emission light source (in a vacuum chamber) demonstrated that the proposed design is viable in practice. Excellent field emission and luminance characteristics were observed. Low-field uniform illumination was demonstrated.

The flat-format design of this FE-lamp represents a robust and low-cost light source with potential for high brightness, variable spectral output, and—if white CL phosphor mixtures are used—tunable color rendering index and/or color temperature. The technique serves as a viable alternative to toxic fluorescent lamps, which contain mercury, and expensive, problematic LED "white lights." The format is applicable to flat-panel LCD display backlights. The ability to manufacture this lamp without microfabrication technology offers a significant cost savings over more complex light sources, such as nitrided-semiconductor LEDs.

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