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Sensors and Actuators 80 (2000) 138–142

SENSORS AND ACTUATORS A PHYSICAL

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Light-emitting devices using micromachined Si-tip mirror arrays

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Received 8 February 1999; accepted 19 July 1999

Abstract

In this paper we introduce a new structure and process scheme to generate visible light by the combination of Si-tip reflectors with thin film electroluminescent structure and report preliminary results of light emission observed from the structure. As a result, 3600 reflectors were formed within one pixel and these picture elements create a well-concentrated visible light around the point reflectors under a bipolar pulse excitation. Even though the absolute luminance level is not very high, this result is very interesting because the front emission observed by a viewer originated intrinsically from the edge emission. The new devices suggested will contribute to the development of a high-bright micro-display with the integrated drivers.

Keywords: Flat-panel display using MEMS technology; TFELD; Micro-mirror; Micro-display; Si-tip

1. Introduction

The use of micro-machining technology in various display applications has increased over the last few years [1–3]. Field emission displays (FED) exhibiting high luminance and ruggedness have become available with an increasing industrial interest in their commercial application. Because FEDs work normally under a high vacuum of 10^{-6}–10^{-7} Torr, vacuum sealing and maintenance is one of the difficult technologies. On the other hand, the thin-film electroluminescent (TFEL) device is a perfect solid-state device without containing vacuum, liquid crystal and plasma. However, the main problem that limits their extensive use in commercial applications is the need for improving the luminance intensity under the sunlight and luminous efficiency of the color devices.

The typical alternating current (AC) TFEL device configuration produced up to this time is a multilayer structure consisting of front transparent glass substrate, a transparent electrode, transparent insulating film, a transparent phosphor, and a reflecting back electrode. The light emitted by the phosphor layer is then observed through transparent electrode and substrate (face emission). However, there had been reports that edge emission could be considerably brighter than face emission [5–8]. For the edge emission, the light-emitting phosphor must also serve as low attenuation waveguide. Thus, the material should have a low absorption coefficient and a high refractive index relative to the substrate. This then produces a highly intense and directed light source. The authors have previously reported a pixel structure comprised of ACTFEL devices with a micro-machined four-sided Si mirror of size 2 mm × 2 mm based on the Steven's concept [3,4]. Efficient EL emission observed from EL array structures was attributed to the efficient reflecting capability of the mirrors and to the long propagating distance of EL light on the order of 40 mm in the electron-beam evaporated ZnS film. While our four-sided Si diaphragm mirrors are useful for investigative studies on the EL pixel using edge emission, they have a limitation in resolution.

An array of cone-shaped micro-tip reflectors such that the light intensity from each EL structure is proportional to the light reflecting on a cone-shaped tip, presents an approach to new EL device. The use of this structure is being extended to nearly sub-micron dimension in order to maximize resolution and luminance by circumventing the need to optimize a mirror dimension in the diaphragm [3]. Such a device could be of considerable importance since a device using tip-shaped reflector does not have a resolution limit as encountered in four-sided mirror planes. Furthermore, the number of reflectors can be increased within the allowed resolution of conventional Si lithography technology. Since a single EL pixel is all bounded by holes a few micrometers separated from reflectors, the effort for

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0924-4247/00/$ - see front matter
PII: S0924-4247(99)00259-9

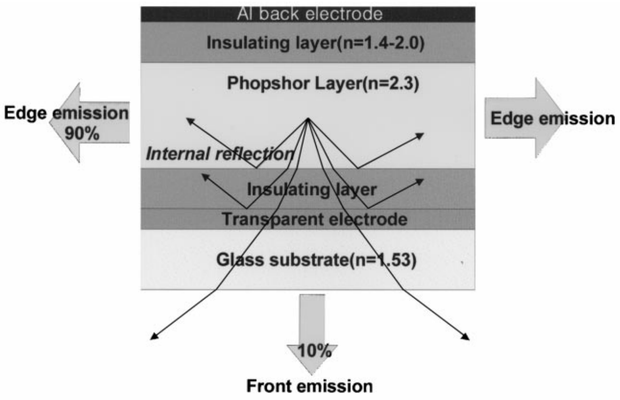

Fig. 1. A schematic scheme for a new light-emitting pixel.

obtaining long propagation distance which was required in four-sided mirror planes was not necessary.

This paper present an improved method which enables more effective reflecting of the edge emission to the front side. In addition, a detailed description of the process sequence involved in fabrication of a cone-shaped Si reflector arrays and the whole structure is presented. Finally, we report preliminary results of light emission observed by TFEL with the tip reflector, and the limitation of the tip-shaped mirror material is discussed.

2. Device fabrication and characterization

The schematic configuration of the suggested light-emitting device is shown in Fig. 1. The process sequence for the pixels utilizing edge emission is illustrated in Fig. 2. The first step for the structure is cleaning of 2–5 Ω cm n-type (100) silicon wafers and oxidizing them to a thickness of 1500 nm. For these high density laterally emitting devices, deposition of electrode material onto the Si substrate would cause a direct electrical contact between adjacent electrodes. The 1-μm thick thermal SiO_2 film was formed at 1100°C by the thermal oxidation as an etching mask as well as electrical insulation between adjacent electrodes. After the growth, the SiO_2 is etched in a reactive etcher using CHF_3/O_2 plasma. The Si (Fig. 2(b)) was etched into tip-shaped patterns using SF_6 and the oxidation for the tip-shaped reflector sharpening followed [4]. The SiO_x as an upper insulator in the TFEL structure is deposited by the electron-beam evaporation (Edwards auto 306A coater) at a substrate temperature of 100°C with a deposition rate of 16 nm/sec. Because oxide films deposited by the electron-beam evaporation method are oxygen deficient and porous, the films must be treated in ambient oxygen. The post-process, i.e., densification, resulted in the increase of the breakdown field strength and reduction of the etch rate in buffered HF to values comparable to that of thermally grown oxide. On the other hand, the SiO_2 is required to have a highly directional growth to keep the sides of the tip-shaped Si planes exposed. In order to achieve the purpose, we used the specially designed substrate holder, which is rotating and tilting simultaneously. In this way we have been controlled effectively the height/width aspect ratio of the TFEL structure. Subsequently 500- and 700-nm thick ZnS:Pr,Ce phosphor film was deposited onto the post-annealed SiO_x lower insulator by the electron-beam evaporation method and then the SiO_x upper insulator onto the phosphor. Finally, buffered HF solution was used to etch away the oxide around the Si reflector. Some over etching was required to form grooves at the sides of the reflector; this completed the fabrication process of high-density TFEL pixels with tip-shaped Si reflectors.

For electrically characterizing the bottom and the upper SiO_x insulating layers the I–V characteristics were measured by a Keithley 237 Source and Measure unit. In order to drive the pixel the standard waveform for driving the pixel was achieved using an arbitrary waveform generator

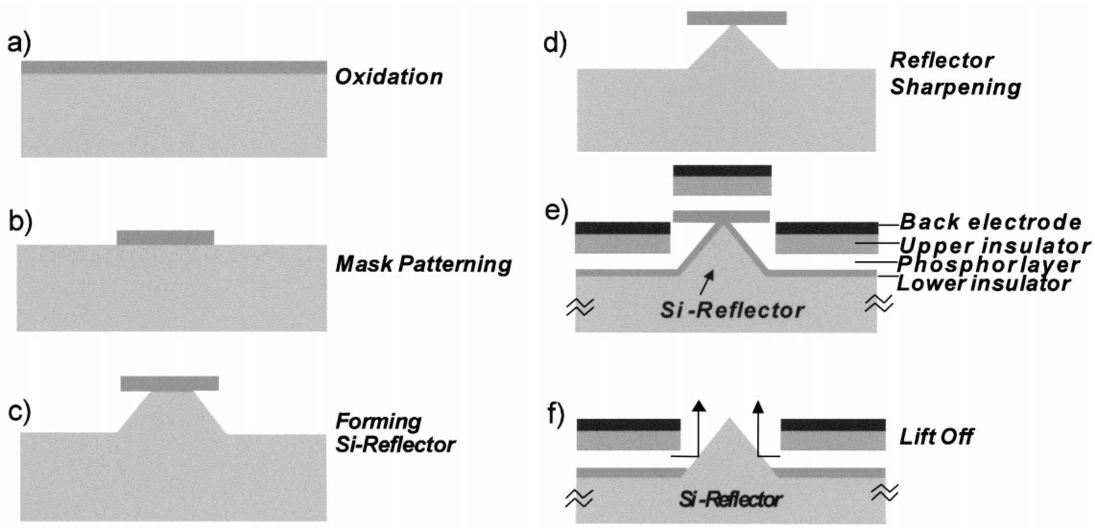

Fig. 2. An illustration of the fabrication steps for the new light-emitting devices.

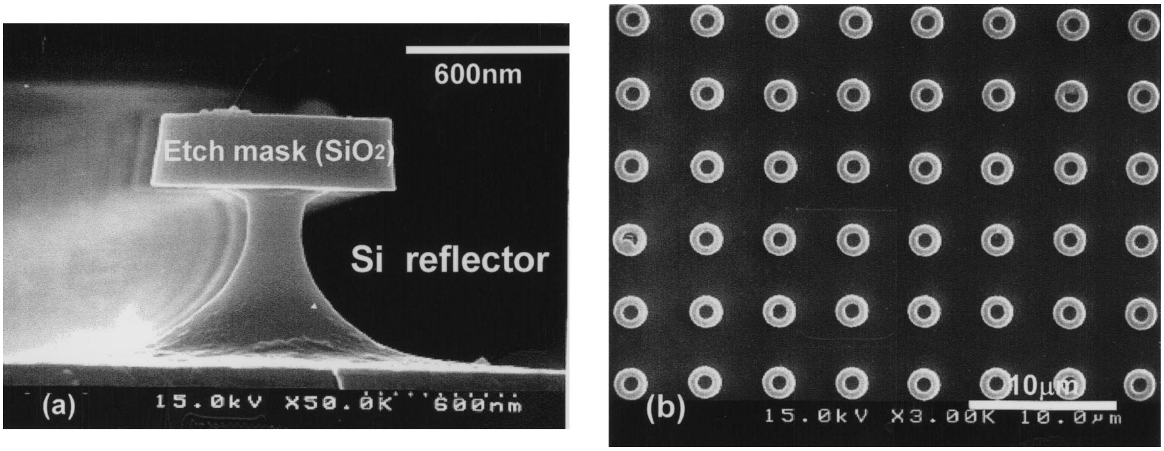

Fig. 3. Microphotographs of a Si reflector with a cap (a) and Si reflector arrays (b).

(HP 33120A) in conjunction with a high-voltage operational amplifier (Apex PA85). The waveform was symmetric with alternating bipolar pulses of trapezoidal shape with 40-μs rise and fall times and a pulse width of 80 μs. The luminous brightness of emitted light from these devices was determined using a fully automated spectrum measurement system and Tektronics J16/J17 luminance meter, respectively.

3. Result and discussion

A SEM microphotograph of the Si reflector with the thermal oxide, is shown in Fig. 3. It clearly shows the well-defined tip-shaped Si reflector with the silicon dioxide cap as a mask and the height of the reflector is about 800 nm. Fig. 4 shows DC current–voltage characteristics for the SiO_x insulator as-deposited and densified in oxygen atmosphere, respectively. The leakage current density was reduced significantly as compared to that of the as-deposited SiO_x layer and the maximum breakdown field strength was well above 6 MV/cm. From this result, we confirmed that the post-annealed SiO_x insulating film is very suitable for the TFEL device working above 2 MV/cm field as well as having advantage of the same e-beam deposition process used for the phosphor.

Fig. 5 shows the microphotograph of a part of a pixel with tip-shaped reflector arrays. The structure has a back electrode (Mo) with a smooth edge and the reflectors are situated exactly at the center of the back electrode opening, as shown in Fig. 5. In the array shown, the spacing between two reflectors is about 4.5 μm and the separation between reflector and back electrode can be scaled down to 1 μm as illustrated in Fig. 5(b).

A common difficulty in the fabrication of FED is uniformity of the tip shape and therefore of electron emission. Here, it is important that the non-uniformity of the tips in this type of new pixel is not a critical factor because tips work only optical reflectors without having electrical functions. Furthermore, because 3600 reflectors are formed within one pixel, geometrical uniformity of an individual reflector is not a problem though uniformity could be assessed visually from the integrated light intensity reflected by the tips. Thus, from Fig. 6 it will be expected that these devices will create a well-concentrated

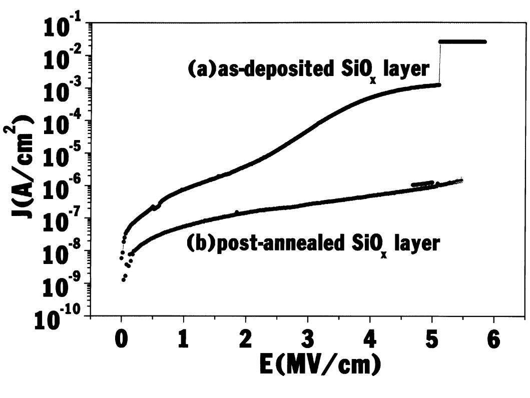

Fig. 4. Leakage current vs. applied voltage characteristics for the SiO_x insulating layer after post-annealing.

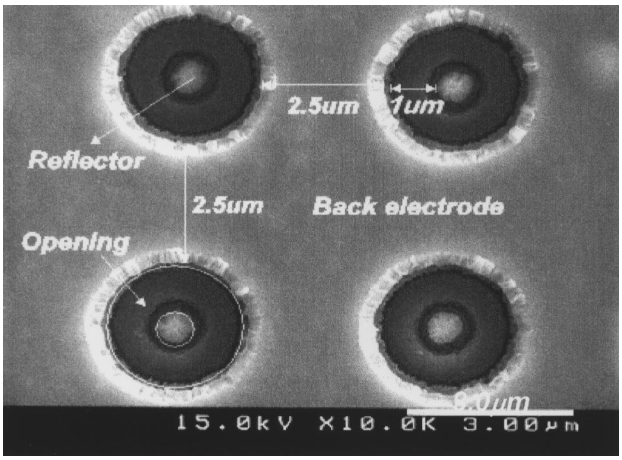

Fig. 5. Front-view of a completed picture element with tip-shaped reflector arrays. One picture element has 3600 reflectors.

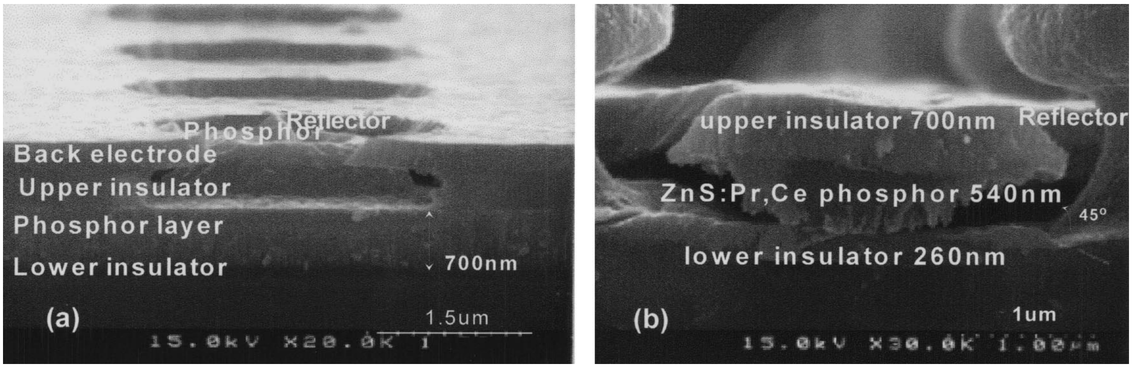

Fig. 6. Cross-sectional view of the completed structure with a reflector (a) and a disrupted structure during etching process (b).

visible light around the point reflectors under the bipolar pulse excitation. Completed devices have reflectors situated at the level of back electrode as presented in Fig. 6(a).

In order to gain more understanding of whether the above beneficial effects are limited to special materials and process conditions, or both, additional experiments will be required. A representative example for the concern is shown in Fig. 6(b) and the microphotograph shows that poly-Si reflectors got damaged during the whole process. It is believed that the damage is due to excessive heat and current after a spark discharging during pixel driving. And also, it suggested that many works should be performed to use conductive material as a reflector as well as column electrode.

There had been reports that edge emission could be considerably brighter than face emission. However, the light-emitting phosphor must also serve as low attenuation waveguide. Thus, the material should have a low adsorption coefficient and a high refractive index relative to the substrate. This then produces a high intensity, directed light source. To obtain the bright edge emission we should bear in mind the fact that as light exists from the emitter, all but the lowest propagation modes become seriously deflected. As the ZnS:Pr,Ce layer becomes thicker, the spread of the angular distribution tends to become wider while in a thinner ZnS layer, the total output is reduced due to the fewer modes of propagation it can support [9,10]. Furthermore, this output is more nearly concentrated in the forward direction instead of edge emission. Therefore, we adopted a relatively thick ZnS layer (700 nm) as compared to a conventional TFEL device using front emission. Under bipolar pulse driving, the threshold voltage for substantial brightness occurred at approximately 160 V_{peak}. As a result, we achieved a visible light emission from the structure as shown in Fig. 7. External view is perfectly same to the front emission in conventional TFEL device because the apex of the micro-tip reflector is several hundred angstroms in diameter. In face emission presented in Fig. 7, the glowing region completely filled the aperture. We measured the light-emitting spectrum as presented in Fig. 8 and confirmed broad spectrum covering whole visible range. Referring to the spectra of the convention TFEL devices utilizing surface emission, it is clear that the obtained emission originates from white-light-emitting ZnS:Pr, Ce phosphor and thus, edge emission of TFEL structure. Although the absolute luminance level is not very high, this result is very promising because the observed light emission is purely edge

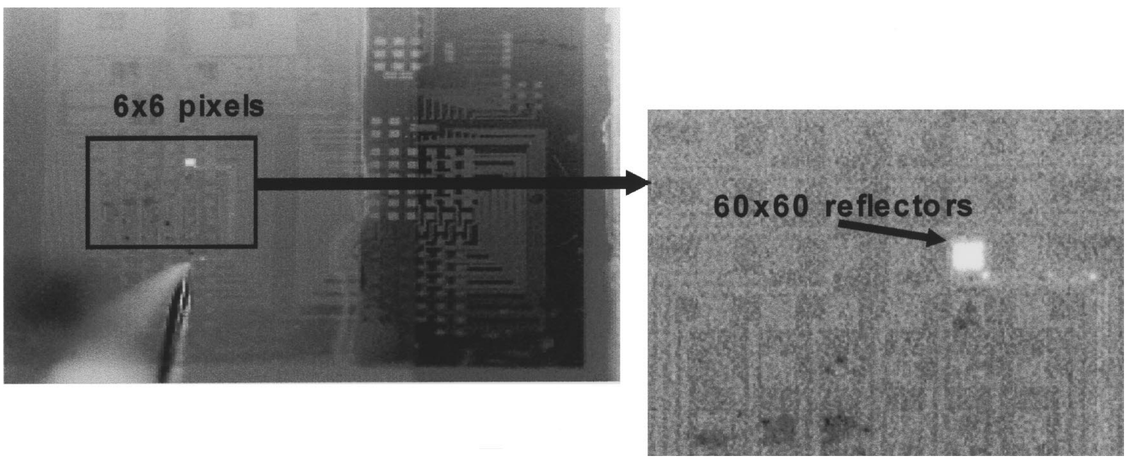

Fig. 7. A photograph of the 6×6 dots new type display structure.

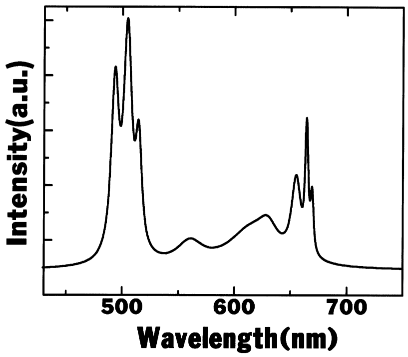

Fig. 8. Light emission spectra for the newly fabricated pixel.

emission, which was neglected in conventional devices. Furthermore, there is a sufficient margin for the improving display quality by optimizing etching processing and material selection. The device structure will contribute to development of a high-bright micro-display with the integrated drivers. Considering the fact that the development of the flat-panel display having features of high luminance and high resolution is required for the micro-display, the light-emitting pixel achieved combined with a conventional front emission structure will be utilized to improve light intensity. Further optimizations and characterization are underway to find more economic processes and materials.

4. Conclusion

A new white-light-emitting device using only edge emission is implemented in combination with the light emission of TFEL structure and reflecting properties of Si-tips. Device consisting of 6×6 pixels has 3600 reflectors within one pixel create a well-concentrated white-light around the point reflectors under the bipolar pulse excitation. (The transferred charge vs. applied voltage characteristics was not generally equal to that of the conventional TFEL device, showing distorted loop.) This could be attributed to the un-etched phosphor layer around conducting Si-tip reflectors, but more experiments were required. Although the electrical characteristics showed some instability and difference as compared to those of the conventional TFELD, luminescence spectrum for the devices was nearly the same as the conventional TFEL devices with a front emission. It was shown in this works that the combination of Si-tip reflectors with a TFEL structure could be used to create a new perfect solid-state light-emitting device. This new device generate the light using purely edge emissions of TFEL structure and also, the process and structure fabricated on Si substrate will enable the integration of driving circuitry on the same wafer.

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