White-Light Emitting Thin-Film Electroluminescent Device Using Micromachined Structure

Yun-Hi Lee, Byeong-Kwon Ju, Man-Ho Song, Dong-Ho Kim, Taek-Sang Hahn, and Myung-Hwan Oh

Abstract—**A white-light emitting electroluminescent (EL) device with newly developed ZnS:Pr, Ce, F phosphor layer was fabricated inside a micromachined well having four-sided Si mirrors, prepared by anisotropic wet etching of Si (100) wafer. Highly luminant EL was achieved using the Si micromirrors. Furthermore, the EL device utilizing the metallized mirrors incorporated into the glass substrates also exhibited enhanced brightness when compared to the conventional face-emitting EL device.**

I. INTRODUCTION

THE head-mounted displays (HMD) directly coupled to the headgear set have shown many potential applications in the area of military, medicine, and entertainment. In order to meet the necessary requirements for the above applications, the HMD must satisfy the following conditions such as light weight, small dimensions, low power consumption, high resolution, high efficiency, ruggedness, etc. [1].

The alternating-current thin-film electroluminescnet (EL) device is a strong candidate for the HMD application. A typical EL device consists of a thin-film phosphor layer interposed between two insulators and two electrodes, thus forming a capacitatively coupled device. Such a solid state nature of EL structure provides low profile, ruggedness, and wide operating temperature range. Recently, the development of the high-resolution active matrix electroluminescnet device (ELD) for the HMD application showed a compatibility between the ELD fabrication technology and the silicon process.

In general, the visible light is emitted from the face (or surface) of the EL structure. Due to high refractive index of ZnS, approximately 90% of the generated light is trapped in the polycrystalline ZnS phosphor layer as the light propagates through the ZnS layer [2]. Recently, enhanced brightness of ELD by improving the emission process and utilizing the wave guide aspects of ELD structure has been reported [3]. There are two methods to achieve highly bright ELD; fabrication of ELD with maximum face emission but without any edge emission, and utilization of the edge emission as the major contribution to the total brightness of a pixel in addition to the face emission. As discussed by Zoltan *et al*. [2], the crystalline quality of the ZnS phosphor layer plays a very important role in the former case by determining the magnitude of the edge emission. The ZnS phosphors deposited by other methods except atomic layer epitaxy showed the higher edge emission than the face emission.

In order to maximize utilizing the edge emission for improving the total brightness of ELD, we have fabricated a highly luminant EL device by applying the known silicon micromachining technology to the fabrication of EL device. Contrary to the ELD using the thin-film SiO_2 mirror planes [1], the edge roughness can be completely eliminated in this case. Furthermore, the mirror profile can be controlled and reproduced with a great accuracy. Since a single EL pixel is all bounded by micromachined silicon crystal planes, the edges of the pixel will be clearly defined due to definite intersection angles between the various surfaces. Here, we present results on the emission characteristics of the edge emitting ELD and the edge-combined-face-emitting ELD fabricated by the Si micromachining technique. Furthermore, as an extension of our work, we fabricated an inverted ELD structure with two-sided metallic mirror walls formed inside a glass grove strip and will discuss about the emission characteristics of this device.

II. FABRICATION OF THE DEVICES AND MEASUREMENTS

The micromirrors are formed on a (100) silicon wafer using the metal mask covering the wafer surface except the diaphragm patterns. The silicon wafer was etched by anisotropic chemical etchant KOH and catalyzed EPW (ethylenediamine-pyrocatechol-water) solution. The details of the etching process were described in our previous papers [4], [5]. After etching the silicon wafer, in order to investigate the compatibility between the EL layers and Si, we deposited a $BaTiO_3$ thin film as the lower dielectric layer of EL structure onto the Si micromachined base. Amorphous $BaTiO_3$ layer was deposited by the radio frequency magnetron sputtering at room temperature onto the whole surface of silicon substrate. A $BaTiO_3$ hot-pressed ceramic disk with 4-in diameter (Cerac Co., USA) was used as a target. The initial vacuum was 5×10^{-5} torr and the working pressure was 8 mtorr including Ar and 10% of O_2 mixture gas. Newly developed white light-emitting ZnS:Pr(0.3mol%), Ce(0.3mol%), F phosphor layer [6] was then deposited by the electron-beam evaporation method and post annealed at 400 °C for one hour under the vacuum. SiO_xN_y thin film, the upper insulating layer, was deposited by the same method as the $BaTiO_3$ thin film. The whole Si surface was covered by the trilayers of $BaTiO_3$, ZnS:Pr, Ce, F, and SiO_xN_y thin films. Finally, either aluminum (ELD 1) or

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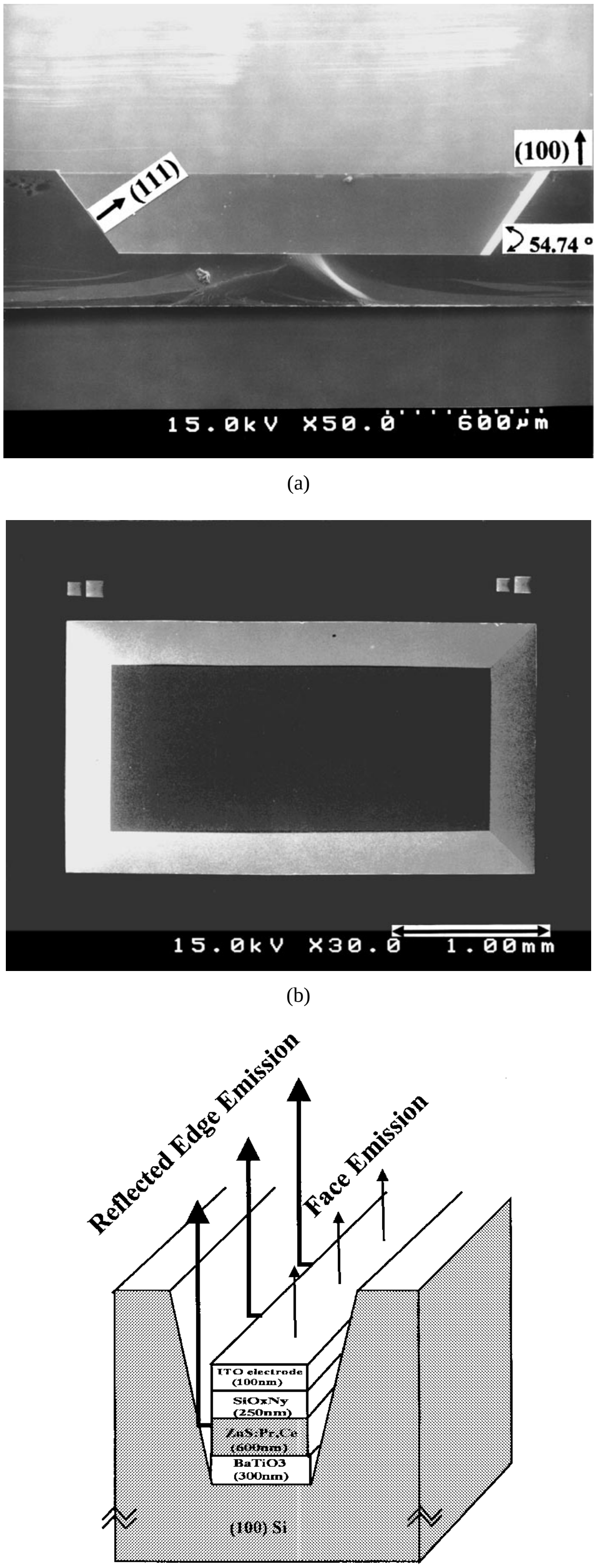


(a)

(b)

(c)

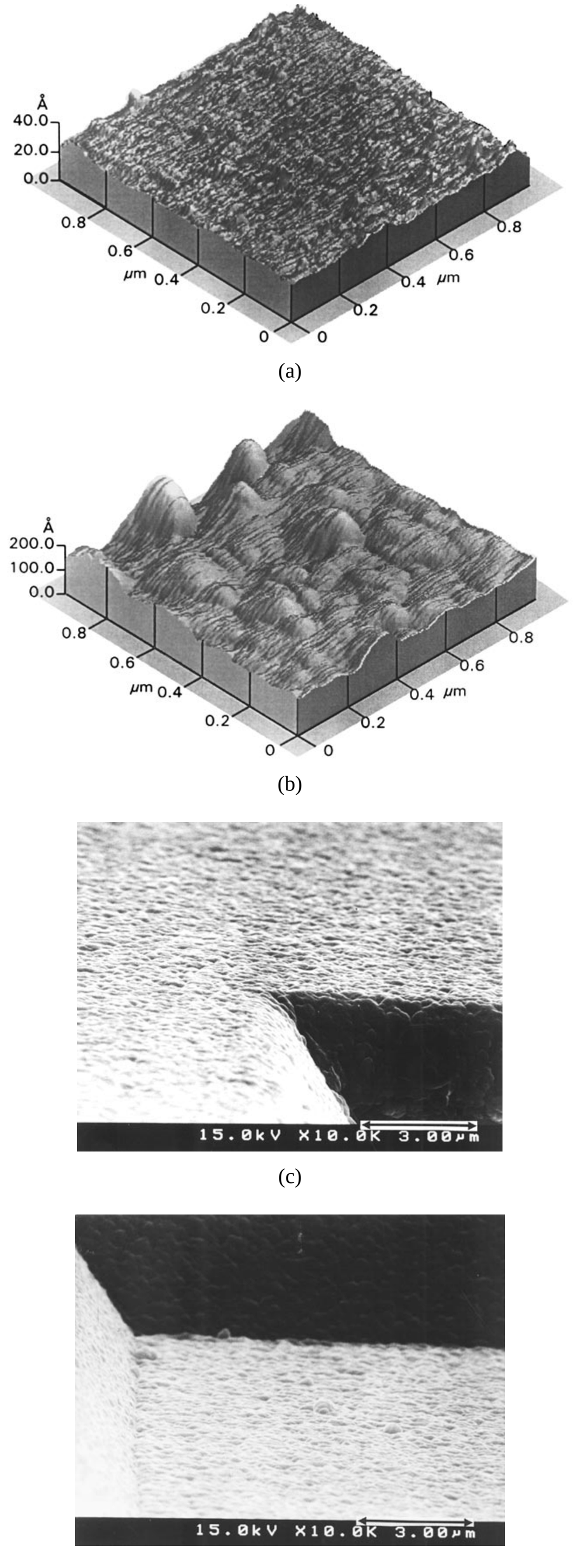
Fig. 1. Schematic structure of our devices: (a) diagram of four-sided Si micromachined mirrors; (b) SEM photograph of four-sided Si micromachined mirror; and (c) schematic of our ELD with Si micromirrors.

transparent Sn-doped In_2O_3 (ITO) film (ELD 2) was thermally evaporated on the top of the prepared devices as the top electrodes in order to study the effect of the micromirrors on the luminance characteristics of EL device. Typical schematic diagram of a single EL pixel is shown in Fig. 1(c). In ELD 1, the emission is only from the edge of the light-emitting layers since the surface emission toward the top layer (Al) is totally reflected, and the emission released from the edge of light-emitting layer was reflected by the four Si mirrors inclined 54.7° from (100) plane, thus the resulting emission is directed upwards. The surface morphology and the structure of the fabricated devices were observed by the scanning electron microscopy (SEM) and the atomic force microscopy (AFM). Average brightness was measured with Tektronix J16 photometer equipped with elastomeric holder for thirty pixels within the area of 2.9 mm^2. The effect of the adding the edge emission to the efficiency of ELD, defined by slope of the light output versus transferred charge curve [6], was investigated by measuring the luminance versus transferred charge $(L\text{-}Q)$ loops using the modified Sawyer–Tower circuit.

III. RESULTS AND DISCUSSIONS

Fig. 1(a) shows the crystallographic diagram of a four-sided silicon micromirror on which the EL structure is constructured. Fig. 1(b) presents a SEM picture for the same four-sided Si micromirror fabricated by the anisotropic etching. The quality of the side-wall micromirrors can be evaluated by the sharpness of the side-wall edges formed by the intersection of the (100) and (111) planes. We can clearly observe the four (111) walls with straight edges. From the atomic force microscopic images, the surface roughness of the Si micromachined structure is found to be higher than that of the bare Si as shown in Fig. 2(a) and (b). To investigate the role of the surface roughness on the growth of upper layers, we looked into the surface morphologies of ELD 1 and ELD 2 by SEM, which are shown in Fig. 2(c) and (d). From the SEM photographs we could not observe any difference by just looking between the surface morphology of the fabricated EL structure on the bare Si and that on the micromachined Si with micromirrors. However, the computed average roughness using the AFM images was increased from 0.1 to 1.6 nm.

Region 1 in Fig. 3(a) shows the face emission only and Region 2 in Fig. 3(b) shows the combined emission from both the edge and the face of EL structure formed on the micromachined Si with four-sided mirror wall in ELD 2. In Fig. 3(b) we observed higher intensity in the side walls since the edge emission is effectively reflected up to the viewer. Fig. 4 shows the typical brightness versus applied voltage characteristics of our devices. In case of ELD 2, when we evaluated the luminance at about 40 V higher than the threshold voltage of each device, the EL pixel with the micromirrors showed a factor of ten times higher luminance level than that from the EL pixel without mirrors. The luminance-transferred charge $(L\text{-}Q)$ characteristics of the fabricated ELD are plotted in Fig. 5. As shown in this figure, the efficiency characteristics of devices with both emissions showed steeper dL/dQ as expected. In spite of the higher rate of light scattering due to rough surface of EL layers formed on the Si micromachined base, the emission from Region 2 shows a factor of about three times higher brightness than that



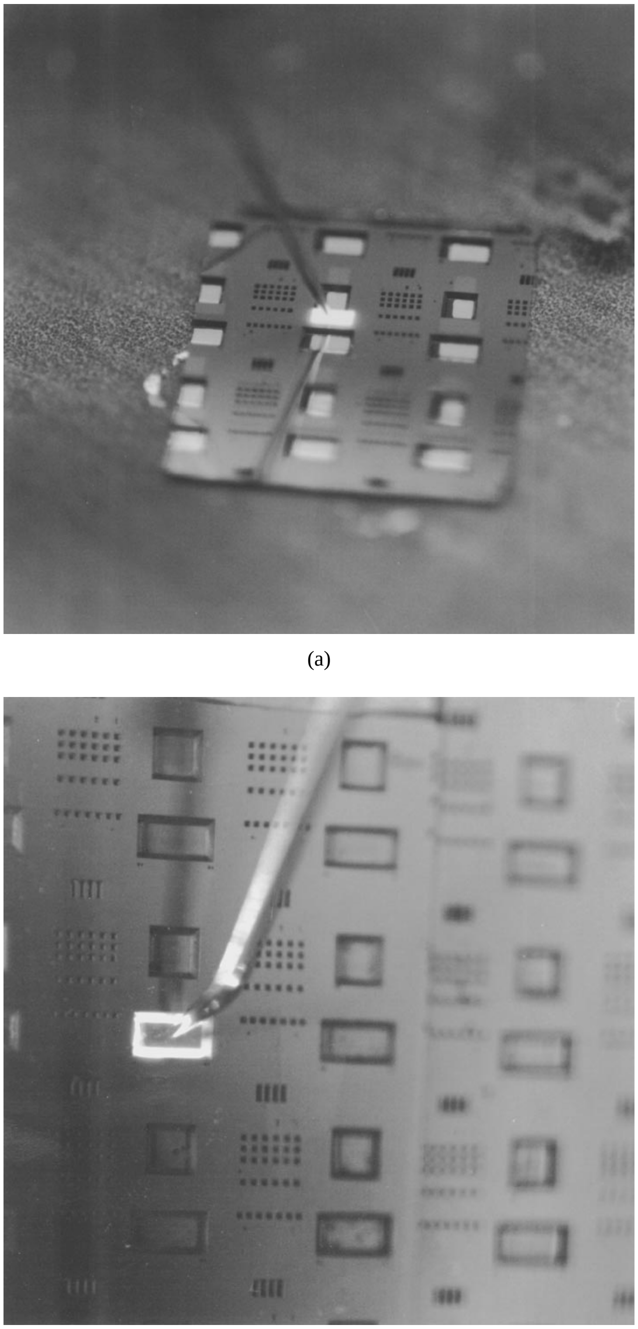
(a)

(b)

(c)

(d)

Fig. 2. Surface roughness measured by atomic force microscopy of (a) unetched Si and (b) micromachined Si mirrors. SEM photograph of (c) the top of the EL structure formed on (a), and (d) the EL structure formed on (b).



(a)

(b)

Fig. 3. Photographs showing light emissions by electroluminescence: (a) The face emission of EL structure and (b) the combined emission from both edge and face of EL structure formed on Si micromachined structure with four-sided mirror walls.

from Region 1 in ELD 2. So far, we have demonstrated that the efficiency of EL device can be significantly improved by combining the edge emission with the face emission.

Extending the above concept, we designed a new structure for the high brightness color ELD with metallic mirrors on the glass substrate (ELD 3). The schematic structure is shown in Fig. 6(a). Since the structure and fabrication process of ELD 1 and ELD 2 are somewhat complex in an aspect of the matrix addressibility, an inverted ELD structure that the EL pixel with metallic mirrors formed on a glass substrate was considered as one of the possible solutions. Grove stripes in glass substrate were formed by the slow etch rate with 70 nm/min in diluted HF solution in order to obtain a smooth surface. The Mo metallic films, as the row electrodes and the metallic mirrors, were deposited into the glass grove and then the normal

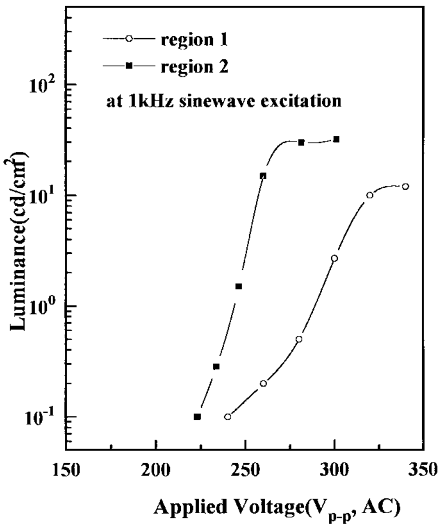


Fig. 4. Luminance-voltage characteristics of the fabricated ELD 2: The open symbols are data obtained from Region 1 and the full symbols indicate the data from Region 2.

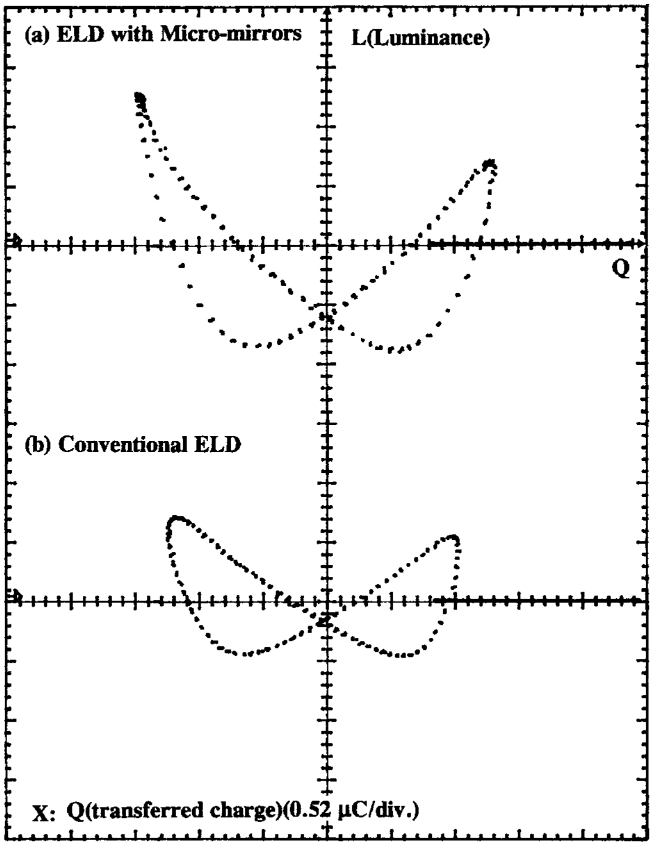
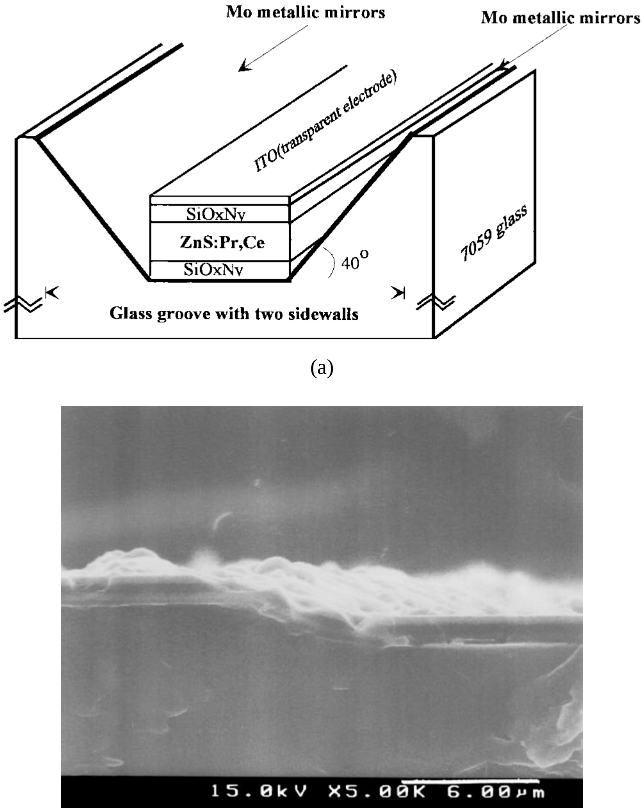


Fig. 5. Luminance-transferred charge characteristics of the fabricated ELD: (a) the EL pixel with four-sided Si micromachined mirrors, and (b) the conventional EL pixel formed on Si substrate.

fabrication process of EL structure was followed. Finally, the 300-nm thick ITO layer was deposited at substrate temperature of 120 °C on the top of the EL layers as the column electrodes by the rf magnetron sputtering. The measured sheet resistance and optical transmittance of the no-annealed ITO layer are in the range of 50–70 Ω/□ and 90–93%, respectively. The



(a)

(b)

Fig. 6. (a) Diagram of ELD with metallic mirrors on the Corning 7059 glass substrate (ELD 3) and (b) SEM photograph of the fabricated ELD.

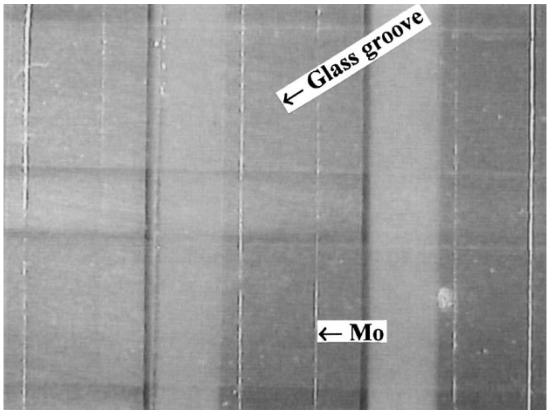


Fig. 7. Optical photograph of the ELD with two-sided metallic mirrors formed on the glass grooves.

cross-sectional view of our new ELD with metallic mirrors is shown in Fig. 6(b). Since the depth of glass grove is about 2 μm and the total thickness of our EL structure including the metallic mirrors is less than 1.5 μm, the emitted light from the edge of the phosphor layer is totally reflected by the Mo mirrors. However, there were few problems, such as rough surface profiles of the glass groove from the wet etching and the subsequent effect on the EL layers. Fig. 7 shows a photograph of the ELD with metallic mirrors formed on the glass grooves.

As shown in Fig. 8, the devices combined with the lateral emission show higher luminance than that of the normal

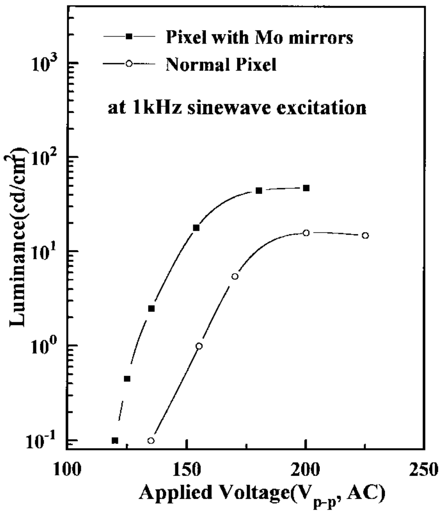


Fig. 8. Luminance-applied voltage characteristics of the inverted ELD structure with the metallic mirrors on the Corning 7059 glass substrate.

inverted EL structure without metallic mirrors. Thus, the feasibility of ELD with the high brightness can be realized by incorporating the reflecting mirrors into the glass substrates along the etched groove strips.

In this work, we confirmed that the two-sided metallized mirrors on the glass grove as well as the micromachined four-sided Si micromirrors can enhance the luminance when compared to the plain dielectric SiO_2 mirror fabricated by Stevens *et al.* [3].

IV. CONCLUSION

In our work, the electroluminescent devices were fabricated inside a micromachined well with four-sided Si mirrors, constructed by anisotropic wet etching of Si (100) wafer. High luminant white-light emitting electroluminescent element was achieved in this case. Furthermore, an inverted EL device structure utilizing the metallized mirrors shaped inside the glass grove strip also exhibited enhanced brightness when compared to the conventional face-emitting EL device. Those ideas would contribute to the development of the low-power consuming color EL device with the high luminance and the high-resolution characteristics.

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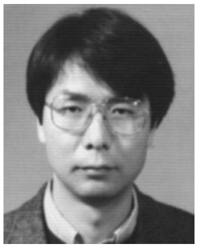

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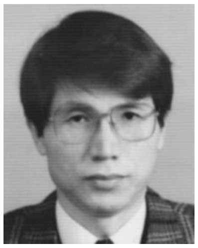

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