Optoelectronic Characteristics of *a*-SiC:H-Based P-I-N Thin-Film Light-Emitting Diodes with Low-Resistance and High-Reflectance N^+-*a*-SiCGe:H Layer

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***Abstract*—The graded-gap a-SiC:H-based p-i-n thin-film light-emitting diodes (TFLED's) with an additional low-resistance and high-reflectance n^+-a-SiCGe:H layer were proposed and fabricated on indium-tin-oxide (ITO)-coated glass substrate in this paper. For a finished TFLED, a brightness of 720 cd/m^2 could be obtained at an injection current density of 600 mA/cm^2, and its EL (electroluminescence) threshold voltage was lowered to 8.6 V. In addition, the effects of reflectance and resistance of a-SiCGe:H film on the performance of TFLED were discussed. The optimum rapid thermal annealing (RTA) conditions for fabrication of TFLED after metallization were also studied and employed to improve the optoelectronic characteristics of TFLED.**

I. INTRODUCTION

SINCE THE success of doping amorphous silicon produced by glow discharge, the related researches of amorphous semiconductors and devices for optoelectronic applications have been developed continuously and have received extensive attention. Because the prime feature of amorphous semiconductors is lack of long-range ordering and structural symmetry, various multicomponent alloys, such as a-SiC:H, which have tailor-made optical bandgaps, can be synthesized. Moreover, in the amorphous semiconductor, the deficiency of long-range periodicity could relax the k-selection rule for optical transition and, hence, results in a large optical absorption coefficient and possibly yields a high luminescent efficiency [1]. One of the optoelectronic devices that nearly utilize all of these advantages is the TFLED.

The studies of EL in amorphous semiconductors have been going on for many years. In 1976, Pankove *et al.* first reported an infrared electroluminescence in a Schottky barrier interface of a-Si:H as well as in an a-Si:H p-i-n junction at low temperature [2], [3]. Since then, the development of p-i-n TFLED's had progressed markedly [4]–[6]. Recently, a series of visible TFLED's made of a-SiC:H have been presented by Hamakawa *et al.* [7]–[10]. The emitting color of TFLED could be controlled from red to orange and to even yellow by adjusting the optical bandgap of the luminescent a-SiC:H i-layer.

As compared with the conventional crystal LED's, the a-SiC:H-based TFLED's possess several potential advantages, e.g., accessible to flat-panel displays, easy to fabricate onto any substrate, tunable color with integrated multilayer structures, and lower cost [10]. The brightness of a-SiC:H-based TFLED, however, is still insufficient for practical applications so far. To increase its EL intensity, the investigations that smooth the potential barriers at the p-i and i-n interfaces [11], [12] or provide a better ohmic contact with external electrodes have been reported [13].

In this paper, a new device structure of a-SiC:H-based p-i-n TFLED was proposed, fabricated, and characterized. In order to increase the carrier injection efficiency and decrease the EL threshold voltage (V_{th}) of the TFLED, the CGL (composition-graded layer) structure [12] was adopted for the depositions of p- and n- layers, and part of the n^+-a-SiC:H layer in the previously reported a-SiC:H-based TFLED [12] was replaced by an n^+-a-SiCGe:H layer, which would lower the internal resistance and increase the internal reflectance of the device due to incorporation of Ge into the film. In addition, the increments of device brightness (B) due to the higher reflectance and lower resistance of the n^+-a-SiCGe:H layer were estimated and discussed. Moreover, to obtain a better ohmic contact for the device, the needed RTA conditions had also been tried.

II. DEVICE STRUCTURE AND FABRICATION

The schematic cross section along with the flow rates of employed source gases and optical-gap diagram of the obtained a-SiC:H-based TFLED having an n^+-a-SiCGe:H layer are depicted in Fig. 1. The numbers in parentheses of Fig. 1(a) are thicknesses of the layers in angstroms. All of the amorphous films in the TFLED were deposited with a plasma-enhanced chemical vapor deposition (PECVD, ULVAC

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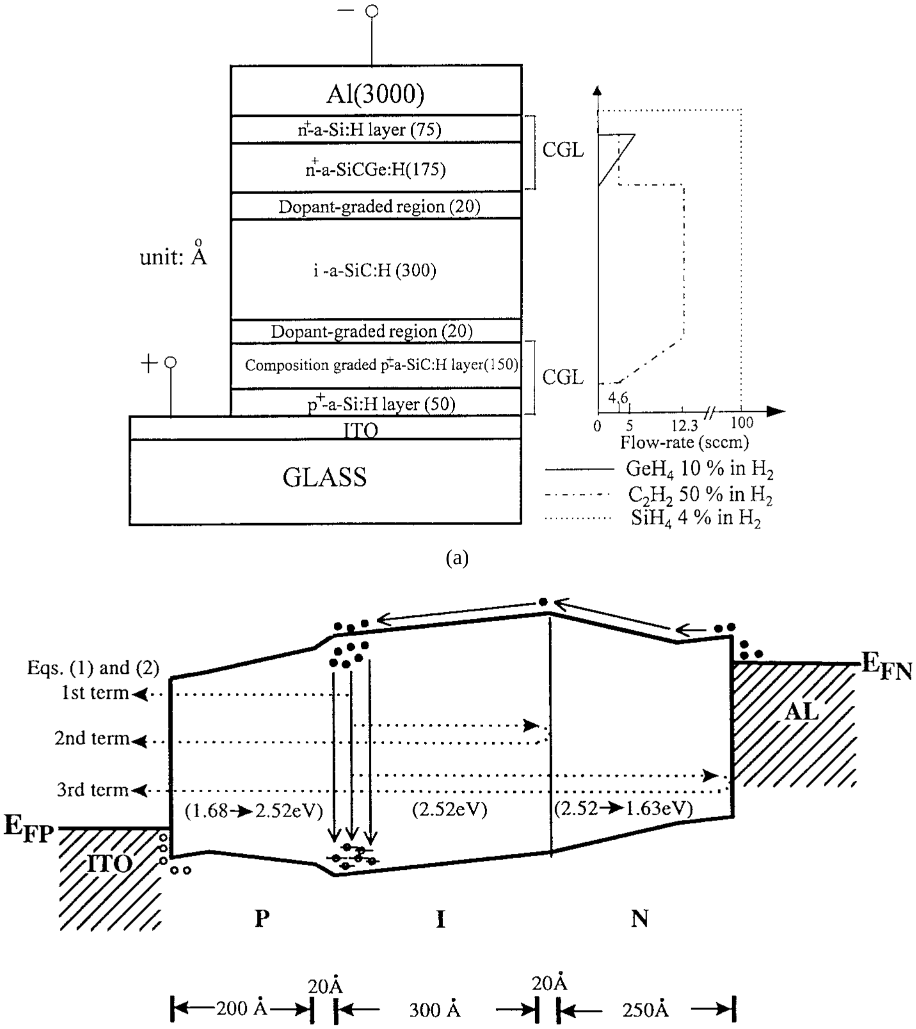

(a)

(b)

Fig. 1. (a) Schematic cross section along with the flow-rates of source gases and (b) optical-gap diagram and the emitting paths of light of the obtained TFLED with an n$^+$-*a*-SiCGe:H layer. The numbers in parentheses of (a) are thicknesses of the layers in angstroms.

CPD-1108D) system. As illustrated in Fig. 1(a), the p$^+$- or n$^+$-type CGL [12] was deposited by suitably changing the flow rates of three source gases (C_2H_2, GeH_4, and SiH_4) to obtain the graded or constant optical bandgap of amorphous films. The p$^+$-*a*-SiC:H CGL was deposited by gradually increasing the C_2H_2 flow rate to grade the optical bandgap from 1.68 to 2.52 eV. The i-*a*-SiC:H layer was obtained by keeping the SiH_4 and C_2H_2 flow rates unchanged to maintain an optical bandgap of 2.52 eV. Similarly, the n$^+$-*a*-SiCGe:H CGL was formed by gradually increasing the GeH_4 flow rate but keeping the C_2H_2 flow rate constant to grade the optical bandgap of this amorphous film from 2.52 to 1.63 eV. Finally, the C_2H_2 and GeH_4 flow rates were down to zero, and the SiH_4 only was used to deposit the thin *a*-Si:H layer, which was used to obtain a lower contact resistance with the external Al electrode than those of the *a*-SiC:H-based layers. As also shown in Fig. 1(a), a dopant-graded layer (DGL) [14]–[17] was formed around the p-i or i-n interface. The DGL was obtained by suitably adjusting the flow rate of doping gas (PH_3 or B_2H_6). All of the deposition parameters of the presented device are listed in Table I. The detailed fabrication processes of the TFLED's having CGL and/or DGL were also described elsewhere [14]–[17].

III. RESULTS AND DISCUSSION

Fig. 2 shows the J (current density)-V (bias voltage) and B-J curves (in the inset) of the obtained *a*-SiC:H-based TFLED with an n$^+$-*a*-SiCGe:H CGL and the previous one [12] with an n$^+$-*a*-SiC:H CGL having the same CGL thickness. As could be estimated from this figure, this new TFLED with an n$^+$-*a*-SiCGe:H CGL had a $B = 720$ cd/m^2 at $J = 600$ mA/cm^2. This brightness was significantly higher than the 400 cd/m^2 for the previous one [12] with an n$^+$-*a*-SiC:H CGL at the same J. The new TFLED had a $V_{\rm th}$ of 8.6 V, which was much lower than that (9.9 V) of the previous one [12]. The $V_{\rm th}$ was defined as the x-axis intercept obtained by linearly extrapolating the linear portion of B-V curve. Therefore, if a thin n$^+$-*a*-SiCGe:H layer was used to replace part of the n$^+$-*a*-SiC:H CGL in the previous one [12], the brightness of *a*-SiC:H-based TFLED would be improved significantly.

The EL spectra for a fabricated TFLED under various bias voltages are depicted in Fig. 3. From this plot, it could be seen

TABLE I
DEPOSITION PARAMETERS OF THE PRESENTED DEVICE

Layer	Source Gases	Flow-Rates (sccm)	Chamber Pressure (torr)
n	$SiH_4 : PH_3$	100 : 72	0.44
	$SiH_4 : C_2H_2 : PH_3$	100 : 4.6 : 72	0.45
	$SiH_4 : C_2H_2 : GeH_4 : PH_3$	100 : 4.6 : 5 : 72	0.47
i	$SiH_4 : C_2H_2$	100 : 12.3	0.35
p	$SiH_4 : B_2H_6$	100 : 36	0.35
	$SiH_4 : C_2H_2 : B_2H_6$	100 : 4.6 : 36	0.38

RF power density = 7 mW/cm^2
Substrate temperaure = 180 °C

Process gases :
1. SiH_4 : SiH_4 (4%) + H_2 (96%)
2. B_2H_6 : B_2H_6 (1%) + H_2 (99%)
3. PH_3 : PH_3 (1%) + H_2 (99%)
4. C_2H_2 : C_2H_2 (50%) + H_2 (50%)
5. GeH_4 : GeH_4 (10%) + H_2 (90%)

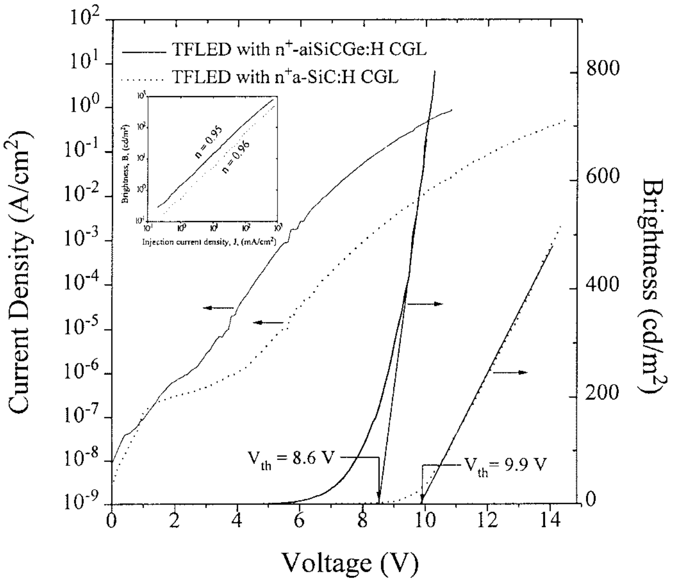

Fig. 2. J-V and B-V (the inset plot) characteristics of the obtained a-SiC:H-based TFLED with a low-resistance and high-reflectance n$^+$-a-SiCGe:H CGL and the previous one with n$^+$-a-SiC:H CGL [12].

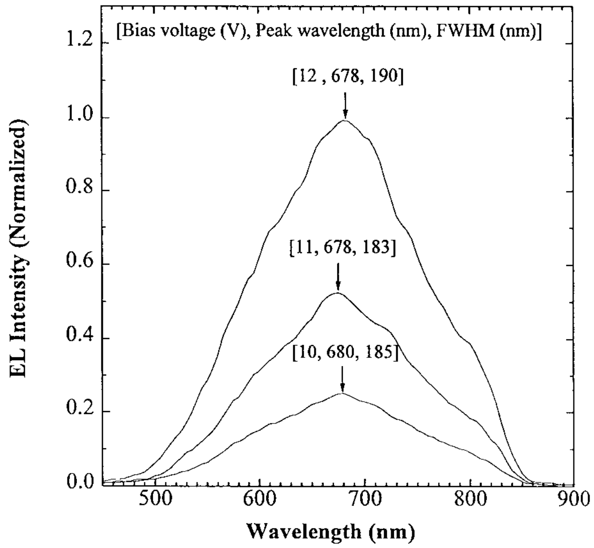

Fig. 3. EL spectra of the obtained TFLED under various bias voltages.

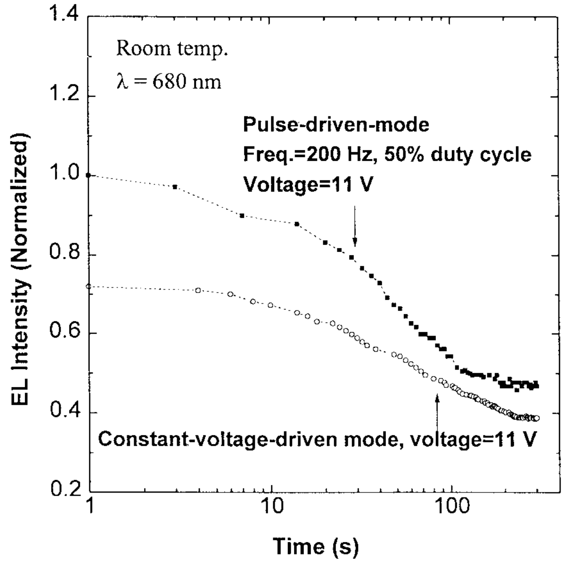

Fig. 4. EL stabilities of the obtained TFLED under 11 V pulse- and constant-voltage-driven modes.

that the peak wavelengths of EL spectra were at about 680 nm. The little blue shift of EL spectrum with the increasing bias voltage, as indicated in Fig. 3, might be due to the fact that some of the electrons could be injected into the higher energy states in the luminescent i-a-SiC:H layer when the TFLED was biased at a higher voltage. The full width at half maximum (FWHM) of the EL spectrum for this TFLED biased at 10 V was about 185 nm.

Comparing the EL characteristics of this new TFLED with the previous one [12], the new (previous) TFLED had a EL peak wavelength at about 680 (586) nm, a EL FWHM of about 185 (140) nm, and a $n = \log(B)/\log(J) = 0.95$ (0.96) (as indicated in the inset of Fig. 2). The wider FWHM and the slightly lower n for the new TFLED indicated that it had a higher probability of tail-to-tail state recombination [9], which would be due to the employed n$^+$-a-SiCGe:H layer having a lower optical gap and a higher defect density. Therefore, as indicated in the inset of Fig. 2, at a constant current density, the increased B for the new TFLED would be due to its wider FWHM of the EL spectrum resulting from its higher probability of tail-to-tail state recombination.

The EL stabilities of this TFLED under the 11 V pulse- and constant-voltage-driven modes had been measured. The TFLED was driven by each bias mode for a total elapsed time of 5 min, and its EL intensity was taken at a 680 nm wavelength, which is about the peak wavelength of its EL spectrum. Fig. 4 illustrates the measured EL stabilities of a typical device. The EL intensity of this TFLED decreased with elapsed time and reached a steady-state value after 2 min at approximately 52 and 45.8% of its initial intensity for pulse- and constant-voltage driven modes, respectively. In this paper, we found the about 10 devices on a substrate that showed similar EL stabilities. This serious problem of EL stability for the obtained device, as compared with the good

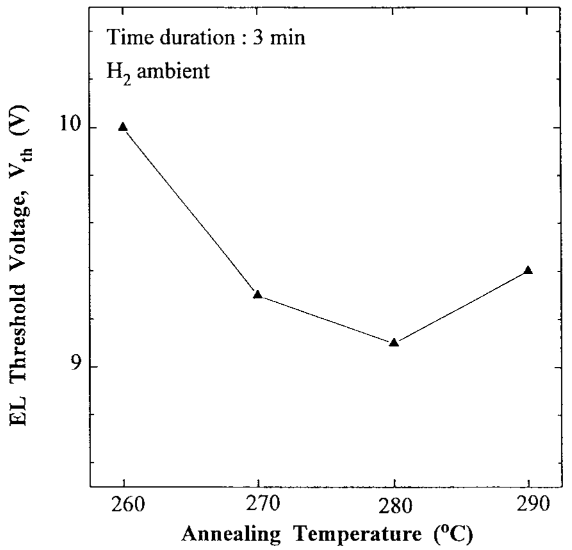

Fig. 5. Variations of EL threshold voltage (V_{th}) of the TFLED's with the annealing temperature ranging from 260 °C to 290 °C.

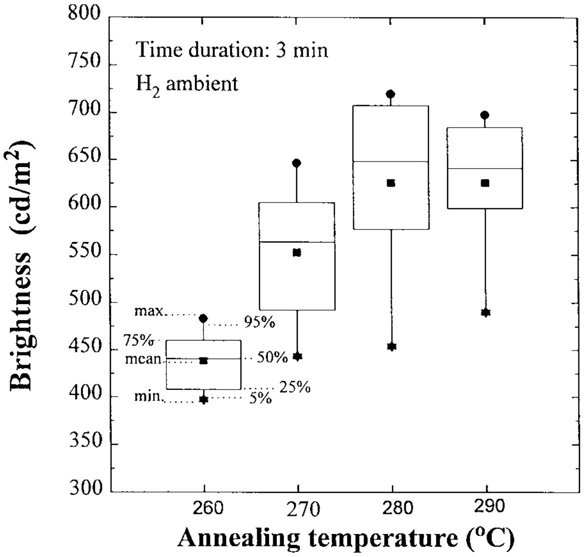

Fig. 6. Variations of brightness (B) of the TFLED's with the annealing temperature ranging from 260 °C to 290 °C.

EL stabilities of the previous one with n^+-*a*-SiC:H CGL [12], might be due to the employed n^+-*a*-SiCGe:H layer and is still under investigation. One of the possible reasons is that the incorporated Ge might be oxidized by O_2 in ambient, and a passivation layer for the TFLED might be needed to improve its EL stability.

To obtain a better ohmic contact between the amorphous layer and external electrode, the annealing process after completing the depositions of needed device layers was studied, and the optimum conditions were used to fabricate the above-mentioned devices. After the last Al metal film had been deposited onto the n^+-*a*-Si:H layer of the device, the sample was put into rapid thermal annealing equipment. In this H_2 annealing process, the annealing temperature and time were chosen independently to obtain a better EL performance of the TFLED. With an annealing process, the adhesion of Al film to the n^+-*a*-Si:H layer would be improved, and the oxide between these two films would be broken [13]. Figs. 5 and 6 illustrate the variations of EL V_{th} and B of the annealed devices with theh temperature ranging from 260 °C to 290 °C. Their annealing time was kept to be 3 min. From Figs. 5 and 6, it could be seen that the B and V_{th} of the annealed devices were improved with increasing temperature up to 280 °C. The annealing temperature should not be more than 290 °C because the H_2 might diffuse out of the amorphous films, and the device's V_{th} was increased, as could be found in Fig. 5. The H_2 outdiffusion would result in an increase of the trap density in the amorphous film, and the degradation of the EL characteristics of the device would be observed [13]. Therefore, a shorter annealing time at higher temperature could not be used in the annealing process.

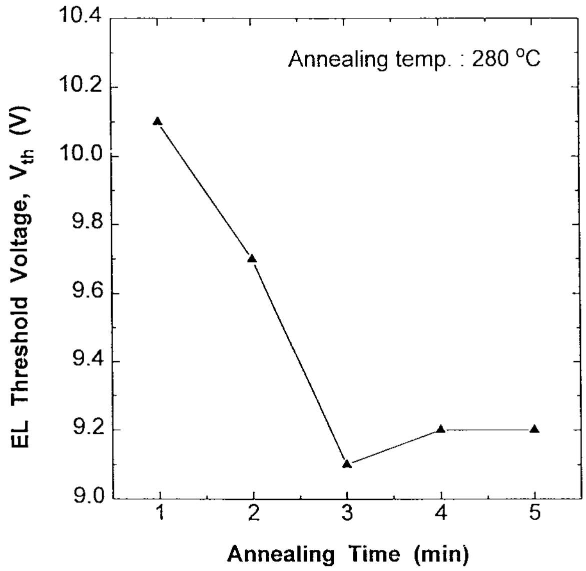

Fig. 7. Variations of EL threshold voltage (V_{th}) of the TFLED's with different annealing time durations.

The variations of V_{th} and B for devices with different annealing times are depicted in Figs. 7 and 8, respectively. Their annealing temperatures were kept at 280 °C. These two plots indicated that the optimum H_2 annealing process for the fabricated TFLED's was a 3-min 280 °C annealing.

The effects of reflectance and/or absorbance of the n^+-*a*-SiCGe:H layer on B of the TFLED are discussed as follows. Both of the device structures for the previous CGL TFLED [12] and this new TFLED could be divided into three regions, where region 1 included the three p-type layers, region 2 consisted of the i-type layer only, and region 3 contained the three n-type layers. The parameters for different regions of the devices are listed in Table II.

The brightness of the previous CGL TFLED ($B_{\rm CGL}$) referring to Fig. 1(b), could be expressed

$$\begin{aligned} B_{\rm CGL} \sim & 0.5 b_{\rm CGL} \exp(-\alpha_1 x_1) + 0.5 b_{\rm CGL} \exp(-\alpha_2 x_2) \\ & \cdot [R_3 \exp(-\alpha_2 x_2) \exp(-\alpha_1 x_1) \\ & + (1-R_3) \exp(-2\alpha_3 x_3) \exp(-\alpha_2 x_2) \exp(-\alpha_1 x_1)] \end{aligned} \tag{1}$$

where $b_{\rm CGL}$ means the initial brightness due to carriers recombined at the p-i interface [10]. In deriving (1), it was

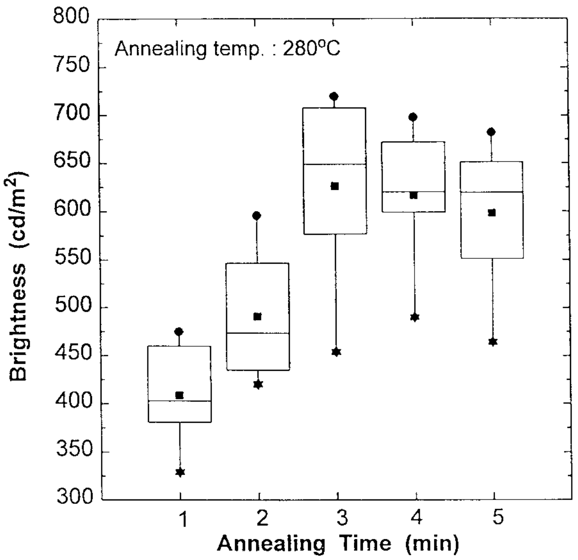

Fig. 8. Variations of brightness (B) of the TFLED's with different annealing time durations.

TABLE II
PARAMETERS FOR DIFFERENT REGIONS OF THE OBTAINED CGL TFLED AND THE PREVIOUS ONE [12]

	region 1 p-layer	region 2 i-layer	region 3 n-layer
CGL TFLED[12]	α_1, x_1	α_2, x_2	α_3, x_3, R_3
The new TFLED	α_1, x_1	α_2, x_2	α_4, x_4, R_4

α : the absorption coefficient

x : the thickness

R : the reflectivity

The subscripts were used to indicate parameters for different regions or materials.

assumed that the photons emitted at the p-i interface went in the backward and forward directions with equal probability, that is, half of light directed to the ITO-electrode side ($0.5b_{\rm CGL}$) and the remaining half directed to the Al-electrode side ($0.5b_{\rm CGL}$). The exponential terms, like $\exp(-\alpha x)$, indicated the light absorption in the amorphous films. In (1), the first term $0.5b_{\rm CGL}\exp(-\alpha_1 x_1)$ was the part of the emitting light directing from the p-i interface to outside. The second term $0.5b_{\rm CGL}\exp(-\alpha_2 x_2)R_3\exp(-\alpha_2 x_2)\exp(-\alpha_1 x_1)$ in (1) was the light directed to the Al-electrode but reflected by the i-n interface to the outside. Finally, the third term $0.5b_{\rm CGL}\exp(-\alpha_2 x_2)(1-R_3)\exp(-2\alpha_3 x_3)\exp(-\alpha_2 x_2)$ $\exp(-\alpha_1 x_1)$ in (1) was the light reflected bythe Al-electrode. Similarly, the brightness of the proposed device with a high-reflectance (HR) n$^+$-a-SiCGe:H layer ($B_{\rm HR}$) could be expressed similarly as

$$\begin{aligned} B_{\rm HR} \sim\, & 0.5b_{\rm HR}\exp(-\alpha_1 x_1)+0.5b_{\rm HR}\exp(-\alpha_2 x_2) \\ & \cdot [R_4\exp(-\alpha_2 x_2)\exp(-\alpha_1 x_1) \\ & +(1-R_4)\exp(-2\alpha_4 x_4)\exp(-\alpha_2 x_2)\exp(-\alpha_1 x_1)]. \end{aligned} \tag{2}$$

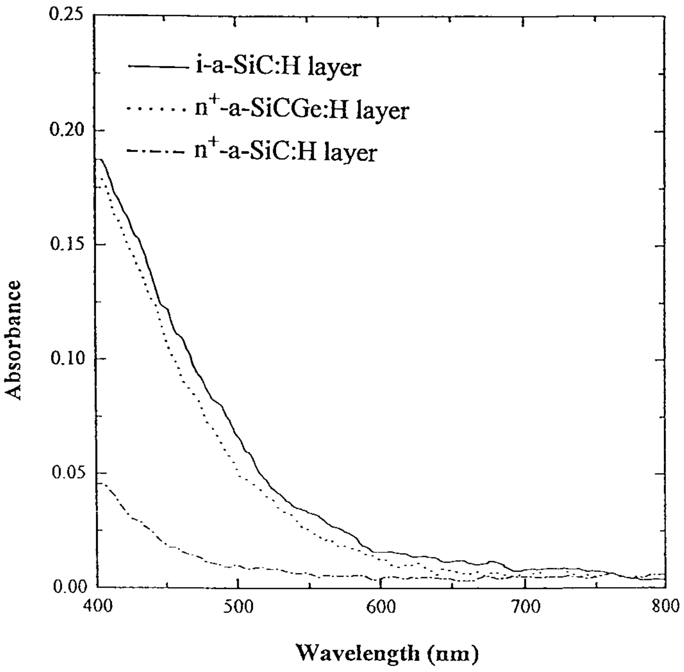

Fig. 9. Absorbances of the i-a-SiC:H, n$^+$-a-SiC:H and n$^+$-a-SiCGe:H layers.

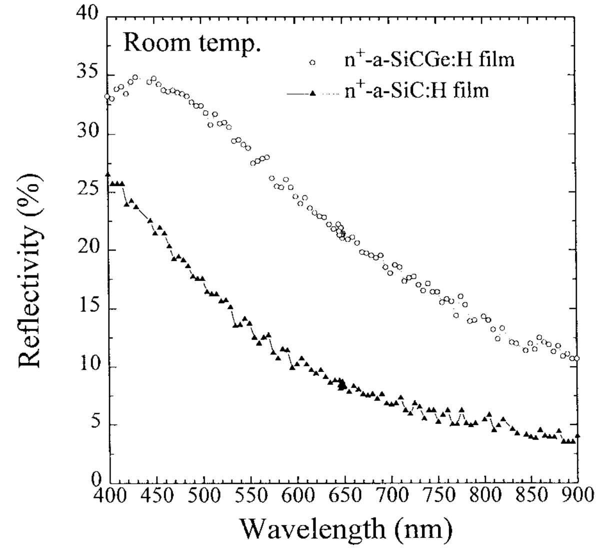

Fig. 10. Reflectivities (in percentage) of n$^+$-a-SiC:H and n$^+$-a-SiCGe:H layers.

The optical gaps, absorption coefficient (α), and reflectivities (R) of amorphous films were obtained with a UV/VIS/NIR spectrophotometer (JASCO V-570). The absorption coefficient of the i-layer, the n$^+$-a-SiC:H CGL layer [12], or the n$^+$-a-SiCGe:H layer for the proposed device could be figured out from $I = I_o\exp(-\alpha x)$, i.e.,

$$\begin{aligned} \alpha &= (1/x)\ \ln(I_o/I) \\ &= (\ln\ 10)[\log(I_o/I)](1/x) \\ &= 2.3025A/x \end{aligned} \tag{3}$$

where $\ln\ 10 = 2.3025, I_o$ is the incident light intensity, I is the light intensity transmitted through the sample, A

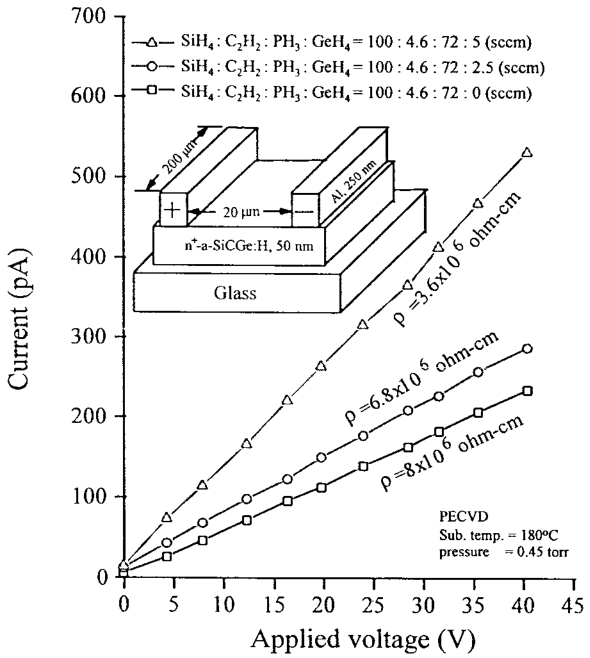

Fig. 11. Current versus applied voltage curves for the n^+-a-SiCGe:H films with different incorporated Ge compositions. The inset plot shows the device structure in this IV measurement.

[defined as log (I_o/I)] which is the absorbance of the film as indicated in Fig. 9, and x is the film thickness. As shown in Fig. 9, there are few differences ($\sim 3\%$ measured at the same thickness of amorphous film) in absorptions of the different films for photons with longer wavelengths including the 680 nm, which was the peak wavelength of device's EL spectrum. On the other hand, as shown in Fig. 10, the n^+-a-SiCGe:H film had a 19% reflectivity at 680 nm, which was higher than that (7%) of the n^+-a-SiC:H CGL. If the obtained α and R were used in (1) and (2), a simple estimation with (1) and (2) would reveal that the improvement of device brightness from the reflectivity of the n^+-a-SiCGe:H layer was lower than 5%. Hence, the contribution of higher reflectivity from the n^+-a-SiCGe:H layer was not sufficient to explain the improved device brightness as indicated by the above-mentioned experimental results because the brightness was increased about 80% (from 400 to 720 cd/m^2). It was worth noting that the reflectivities in Fig. 10 were measured from air-semiconductor interfaces. These reflectivities were higher than those at the interface between two semiconductor layers in actual devices. Therefore, the actual reflectivities in devices (estimated to be about 4% [18]) would be smaller than those in Fig. 10. However, this smaller reflectivity in the device could indicate that the improved brightness of the device was not mainly due to the higher reflectivity of the n^+-a-SiCGe:H layer. Thus, we thought the dominant factor of brightness enhancement for the obtained device might be due to the increased ratio of $b_{\rm HR}/b_{\rm CGL}$.

In order to estimate the resistances of n^+-a-SiCGe:H films with different Ge compositions incorporated, various n^+-a-SiCGe:H films were deposited with different flow rates of GeH_4 and constant flow rates of SiH_4, C_2H_2 and PH_3. As shown in Fig. 11, a high Ge content could be used to significantly lower the resistance of the n^+-a-SiCGe:H film. Therefore, the improvements for EL intensity and $V_{\rm th}$ of the proposed device would be mainly due to the lower series-resistance of the n^+-a-SiCGe:H CGL layer. With this layer, more electrons could be injected into the i-layer and then recombine with holes at the p-i interface to enhance the device EL brightness $(b_{\rm HR})$.

IV. CONCLUSIONS

The a-SiC:H-based TFLED with a low-resistance and high-reflectance n^+-a-SiCGe:H CGL layer led to improved brightness and threshold voltage as compared with the conventional device with an n^+-a-SiC:H CGL. The obtained TFLED fabricated with an optimum 3-min 280 °C annealing process had an obtainable brightness of 720 cd/m^2 at an injection current density of 600 mA/cm^2 and a threshold voltage of 8.6 V. These EL characteristics were much better than those of the previously reported a-SiC:H-based TFLED without Ge composition [12]. The improvements of optoelectronic characteristics for the proposed TFLED were partially due to the higher reflectance of the n^+-a-SiCGe:H layer; however, the lower series resistance of the n^+-a-SiCGe:H layer would be the dominant factor to improve the device EL intensity.

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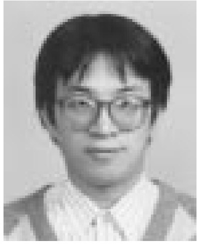

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Li-Hong Laih, for photograph and biography, see p. 570 of the April 1997 issue of this TRANSACTIONS.

Jyh-Wong Hong, for photograph and biography, see p. 570 of the April 1997 issue of this TRANSACTIONS.

Chun-Yen Chang (F'88), for photograph and biography, see p. 571 of the April 1997 issue of this TRANSACTIONS.