Abstract—A-SiC:H p-i-n thin-film LED’s (TFLED’s) containing a single graded-gap p-i-n junction (SG) or double graded-gap p-i-n and i-n junctions (DG) have been postulated and fabricated successfully on indium-tin-oxide (ITO)-coated glass substrates, with a plasma-enhanced chemical vapor deposition (PECVD) system. Some important characteristics and related physics of these two types of TFLED’s are presented and discussed. At an injection current density ($J$) of 600 mA/cm$^2$, the brightness ($B$) of the SG and DG TFLED’s obtained were 30 and 207 cd/m$^2$, respectively. This significant improvement of brightness, as compared to those of the previously reported TFLED’s with a highest brightness of 20 cd/m$^2$, could be ascribed to the reduced interface states with the graded-gap junctions, lower contact resistance between ITO and p-layer due to a plasma treatment of ITO prior to p-layer deposition, post metallization annealing of thermally evaporated Al on n-layer, and higher optical gaps ($E_{gap}$’s) of the doped layers employed. The slopes of the nearly linear $B$–$J$ relationships show the diode factor very close to unity for the fabricated SG and DG TFLED’s. This implies that the electroluminescence (EL) mechanism of these TFLED’s might be a tail-to-tail-state recombination. In addition, the conduction currents of these TFLED’s are almost temperature dependent, and that of the DG TFLED might consist of an ohmic current and a space-charge-limited current (SCLC) within the lower and higher applied-bias regions, respectively.

I. INTRODUCTION

With a lack of long-range ordering with structural symmetry, various multi-component amorphous semiconductors having tailor-made optoelectronic properties can be produced. Its deficiency of long-range periodicity also relaxes the $k$-selection rule for optical transition. This results in an increase of optical absorption coefficient, and could be used to yield a high luminescence efficiency [1].

Infrared electroluminescence (EL) in a Schottky-barrier interface of $\alpha$-Si:H at low temperature was first reported in 1976 [2], and then also observed in an $\alpha$-Si:H p-i-n junction [3]. After that, various visible a-SiC:H-based thin-film light-emitting diodes (TFLED’s) were developed [4]–[10], including basic p-i-n [4], p-i-n embedded with hot-carrier tunneling injectors (HTI’s) at p-i and/or i-n interfaces [5], p-i-n with microcrystalline (μc-) $\alpha$-Si:H layer [6], μc-$n$-$\alpha$-Si:H layer [7], $\alpha$-SiC:H/μc-$\alpha$-Si:H luminescent multilayer [6], i-$\alpha$-SiN:H luminescent layer [8], n-$\alpha$-Si:H layer deposited with heavy H$_2$-dilution process [9], and μc-$n$-μc-$\alpha$-Si:H layer [10]. Among these TFLED’s, the maximum achievable brightness ($B$) reported is around 20 cd/m$^2$ at an injection current density ($J$) of 1000 mA/cm$^2$ [5].

The EL of a forward-biased basic p-i-n $\alpha$-SiC:H TFLED comes from radiative recombination of carriers in the luminescent i-layer. However, due to the limitation of valence-electron controllability, there is a notch barrier at the p-i and i-n junctions, respectively. These notch barriers retard the carrier transport and hence the EL intensity is weak [4]. Therefore, it is necessary to reduce notch barriers to enhance carrier transport and hence obtain a higher EL intensity at a lower forward-bias of TFLED. Consequently, a single graded-gap (SG) p-i interface can be used for improving the brightness of an $\alpha$-SiC:H p-i-n TFLED [11], since the increased hole current plays an important role in radiative recombination and, hence, EL properties of TFLED’s [5], [11]. In addition, a double graded-gap (DG) structure which has graded-gap p-i and i-n interfaces enhances the device brightness significantly and reduces its EL threshold voltage ($V_{th}$) substantially [12]. As compared to the complex fabrication process for the $\alpha$-SiC:H TFLED with barrier-layer structures [5], [9], the simple fabrication process for the graded-gap structures provide a higher benefit and reproducibility in production. The characteristics of these two kinds of $\alpha$-SiC:H TFLED’s, such as $I$–$V$ and $B$–$J$ relationships, EL spectra, current-conduction mechanism, and stability are presented in detail in this paper.

II. DEVICE FABRICATION

A schematic cross section of the DG TFLED is shown in Fig. 1 [12], whereas that for the SG TFLED has only a single graded-gap junction at the p-i interface and its i-layer thickness is 470 Å [11]. After a standard cleaning process, an indium-tin-oxide (ITO) coated glass substrate was transferred into a plasma-enhanced chemical vapor deposition (PECVD) system (ULVAC CPD-1108D) which was used for depositing various amorphous thin-films. The deposition conditions and optical gaps ($E_{gap}$’s) of various layers for the SG and DG TFLED’s were listed in Table I.
Before depositing the p-α-SiC:H layer of DG TFLED’s, H₂-plasma bombardment to the ITO surface in the PECVD system was used for reducing the contact resistance between the ITO electrode and p-layer [12], [13]. It was found that the contact resistance between p-layer and ITO electrode was 20 Ω-cm without H₂-plasma treatment, and reduced to 0.5 Ω-cm with H₂-plasma treatment. This can be ascribed to a) the stabilization effect resulting from the reaction of hydrogen links with silicon dangling bonds on the surface being covered with hydrogen atoms, and b) the cleaning effect coming from the reactive hydrogen interacts with impurities on the surface, such as oxygen and carbon, and then removes them by cleaning volatile species [13]. The reason to replace the CF₃-O₂-plasma treatment, which was used in fabrication of the SG TFLED [11], by an H₂-plasma treatment is that it has less contamination to the following films to be deposited [13], [14].

To obtain the higher $E_{opt}$’s of doped layers and hence lower the barrier height at p-i interface, the carbon source gas was used was C₃H₂ rather than CH₄ [4], since the α-SiC:H film deposited with C₃H₂ has a small $E_{opt}$-narrowing caused by boron doping and also a higher conductivity than that of the one deposited with CH₄ [15]. It is found that the luminescence intensity of the deposited film increases with decreasing RF power [16]. Therefore, the used RF power density was decreased from 64 mW/cm² for the SG TFLED to 16 mW/cm² for the DG TFLED’s. The $E_{opt}$’s, determined from individual Tauc’s plots [17], of different layers for the SG and DG TFLED’s are also summarized in Table I. As also observed in our laboratory, the i-α-SiC:H layer deposited with a lower RF power density tended to have a higher $E_{opt}$ than that of the one deposited with a higher RF power density. Experimentally, the i-α-SiC:H layers deposited with 4% SiH₄ in H₂ (200 sccm) and pure C₂H₂ (6 sccm) had $E_{opt}$’s of 2.50 and 2.57 eV for used RF power densities of 64 and 16 mW/cm², respectively.

After depositing all of the α-SiC:H layers, an Al film was thermally evaporated onto the n-layer, through a metal mask, to form contact electrodes. Finally, the device was annealed in an H₂ ambient with an ULVAC TA-7000 rapid thermal annealing (RTA) system to improve the contact between the Al electrode and n-layer [12].

The finished devices were then characterized and their performances were compared. The presented EL data in this paper were the best one among at least ten devices of the same structure, and the performance variation of the successful devices was within 10%.

### III. DEVICE OPERATION

Fig. 2 shows schematic optical-gap diagrams under thermal equilibrium and forward-bias conditions for the SG and DG TFLED’s. The optical-gap diagrams of the SG TFLED were similar to those of DG one, except that the $E_{opt}$’s of employed α-SiC:H layers were different and there was a potential step at the i-n interface as indicated by the dash lines.

For a basic p-i-n α-SiC:H TFLED, when the used carbon-source gas is CH₄, the $E_{opt}$’s of doped layers are limited to 2.0 eV due to valency-electron controllability, while the i-layer $E_{opt}$ can be 2.5 eV or more [4]. Consequently, as above-mentioned, notch barriers exist at the p-i and i-n interfaces [5]. It has been reported by D. Kruangam et al. [4], [5] and also H. Mimura et al. [18] that the notch barrier $\Delta E_{val}$ at the p-i interface is about three times larger than that $\Delta E_{val}$ at the i-n interface. Those band discontinuities at the p-i and i-n hetero-interfaces in α-SiC:H p-i-n junction were determined by means of the internal photoemission from the structures of Au/i-α-SiC:H/p-α-SiC:H and Au/i-α-SiC:H/n-α-SiC:H. In their determination, the $\phi_{int}$-intercept in a plot of (photoelectric yield)$^{1/3}$ versus photon energy gives the threshold photon energy which is equal to the sum of the optical gap of the n- or p-layer and the valence-band’s discontinuity $\Delta E_{val}$. According, the estimated band discontinuities were $\Delta E_{val} = 0.75$ eV and $\Delta E_{val} = 0.125$ eV for the SG TFLED, and on the other hand, $\Delta E_{val} = 0.105$ eV and $\Delta E_{val} = 0.0525$ eV for DG1 TFLED.
IV. DEVICE CHARACTERISTICS

A. J-V_a Characteristics and EL Intensities

The relationships of EL intensity (I_{EL}) and injection current density (J) versus applied voltage (V_a) for the DG1, DG2, and SG TFLED’s had been presented in [11] and [12]. For the DG1 TFLED, J increased rapidly when V_a exceeded 6.5 V, where J_{EL} began to increase. The J-V_a and J_{EL}-V_a behaviors of the DG2 TFLED were similar to those of the DG1 TFLED. Since the i-layer E_{opt} of the DG2 TFLED was higher, its J was lower than that of the DG1 device under a certain V_a. The SG TFLED had a higher injection current density than those of the DG TFLED’s, within the lower applied voltage region. This could be ascribed to its lower i-layer E_{opt}, and hence lower resistivity, than those of the DG TFLED’s. The EL threshold voltages V_{th}’s, where V_{th} was defined as the x-axis intercept of the straight portion of the I_{EL}-V_a curve, were 11.2 V for the DG1 TFLED and 13.8 V for the DG2 TFLED, which were significantly lower than 32 V for the SG TFLED. This may be due to the incorporation of double graded-gap junctions, and the smaller i-layer thickness (300 Å) of the DG TFLED’s. Also, the used step-gap i-n junction of the SG TFLED would degrade its EL property and result in an increase of its V_{th}.

We used an Oxford 1714 temperature-controlled liquid-N_2 crystat system to measure the device characteristics under various operating temperatures (T’s). If the log(J/V_a^2) versus (1/V_a) relationship of the SG TFLED at a certain temperature was checked by following the Fowler–Nordheim (F–N) formula for about V_a ≥ 27 V (1/V_a ≤ 3.6 × 10^{-2} V^{-1}), then, as shown in Fig. 3, a fairly linear dependence was found [11]. However, this dependence on temperature implied its dominating electron current was not simply a F-N tunneling current, which is essentially temperature-independent [19], when V_a exceeded about 27 V. The injection current within the low bias region for the SG TFLED was essentially a thermionic emission current [11]. As shown in the inset of Fig. 3, I_{EL} of the SG a-Si:C:H TFLED at a certain J increased with decreasing T.

Fig. 4 shows the J-V_a relationships of the DG1 TFLED, which were also temperature-dependent and similar to those of the SG TFLED. As obviously depicted in the inset of Fig. 4, the I_{EL} of DG1 TFLED at a certain J also increased with decreasing T. This phenomenon implied the radiative recombination efficiency at a lower temperature was higher.

B. Carrier Transport Mechanism

The conduction currents of the SG and DG TFLED’s were temperature-dependent as mentioned above, so their conduction current possibly includes other current components or is dominated by other current transport mechanisms. In this section, only the J-V_a characteristics of the brighter DG TFLED was investigated from the point view of the space-charge-limited current (SCLC).

Referring to the schematic optical-gap diagram of the DG TFLED as shown in Fig. 2 under thermal equilibrium, there was a 1.6 eV difference in the electrostatic potentials of the n- and p-regions [12]. The injection current of the DG1 TFLED...
increased very rapidly when \( V_a \) increased from 0 to 1.6 V. At \( V_a = 1.6 \) V, the flat-band condition was achieved. For \( 1.6 \) V < \( V_a < 8 \) V, the injection current could become a SCLC with traps [17], [21], [22], and the Ohm’s law would be observed because of the presence of thermally generated free carriers with a concentration \( n_0 \) in the amorphous material [21], [22]. At \( V_a = 8 \) V, the trap-filled limit of amorphous semiconductor was reached. As \( V_a > 8 \) V, the average injected excess free-carrier concentration \( n_i \) could become comparable to \( n_0 \), a dominant single-carrier (electron) injection trap-free

C. EL Spectra

The EL spectra for the SG, DG1, and DG2 TFLED’s can be found in [12] and [13]. The peak wavelength of EL spectrum of the SG TFLED (with an i-layer \( E_{opt} \) of 2.50 eV) located at 710 nm, which was in the red-light region. Its full width at half maximum (FWHM) was 230 nm. A red-orange color was observed by naked eyes, experimentally.

For the DG1 TFLED (with an i-layer \( E_{opt} \) of 2.61 eV), the EL spectrum peaked at 680 nm with a FWHM of 215 nm.
and revealed an orange color. On the other hand, the EL spectrum of the orange DG2 TFLED (with an i-layer $E_{opt}$ of 2.65 eV) peaked at a longer wavelength (700 nm) and had a broader emission band (FWHM = 240 nm) than that of the DG1 TFLED. Such broad spectra of light emission could be primarily due to the wider energy-range of localized states in the i-$\alpha$-SiC:H which had a higher carbon content and hence a higher $E_{opt}$. Also, the broader FWHM of the SG TFLED than that of the DG1 TFLED could be ascribed to the higher RF power density in thin-film depositions which increasing the defect density [15].

The EL spectra of these TFLED’s peaked at around 1.7 eV, which was much lower than that of the $E_{opt}$ of luminescent i-layer. This could be due to that the radiative recombinations were via the broad localized states in the amorphous i- and/or p-layers.

**D. Stability**

It was found that the EL intensity of DG1 decreased gradually within the first 1 min. from the beginning of operation. Then, its EL intensity becomes stable and almost keeps at a steady-state value of about 93% of the initial value when the driving time exceeding 5 min.

**V. BRIGHTNESS COMPARISON**

Fig. 6 shows the brightness ($B$) comparison of $\alpha$-SiC:H basic p-i-n, HTI [23], SG, DG1, DG2, TFLED [11], [12], and packaged HP HLMP 8405 ultra-bright DH AS (double heterostructure on an absorbing substrate) AlGaAs orange LED. The DG TFLED’s had much higher $B$ than that of the SG TFLED, which was primarily due to the improvements of injection current and radiative recombination, as mentioned in Section III. For the DG1 TFLED, the $B$ was 140 cd/m$^2$ at $J = 600$ mA/cm$^2$. The DG2 TFLED revealed a $B$ of 207 cd/m$^2$ at the same $J$. The higher brightness of the DG2 TFLED as compared to that of the DG1 TFLED could be due to the wider energy-range with more localized states in the i-layer which increased the recombination probability. The $B$-$J$ relationship of an $\alpha$-SiC:H TFLED can be expressed as: $B = Jn$, where the exponent $n$ is 1 for a monomolecular recombination, 2 for a bimolecular recombination, and $0 < n < 2$ for a tail-to-tail-state recombination [4]. From Fig. 6, the estimated $n$’s were very close to 1 for these $\alpha$-SiC:H TFLED’s, while the $n$ value of the HP LED was 1.65. This revealed that the EL mechanism of the $\alpha$-SiC:H TFLED’s was due to the tail-to-tail-state recombination [4]. But, the EL mechanism of the HP LED was more closer to the bimolecular recombination.

**VI. CONCLUSION**

We have greatly improved the EL intensity of $\alpha$-SiC:H p-i-n TFLED’s by using the graded-gap junction. For instance, the brightness for the SG TFLED was 30 cd/m$^2$ at $J = 600$ mA/cm$^2$, which was more than two orders of magnitude higher than that of a basic p-i-n TFLED at the same injection current density. The highest brightness obtainable was 140 cd/m$^2$ for the DG1 TFLED and 207 cd/m$^2$ for the DG2 TFLED at the same injection current density. Further, the EL $V_{th}$’s of $\alpha$-SiC:H TFLED’s were significantly lowered by the adoption of graded-gap junctions. We ascribed the significant improvement of brightness and lowering of EL threshold voltage to the enhancement of carrier injection efficiency by introducing the graded-gap structures, the reduction of contact resistances by using in-situ H$_2$-plasma-treated ITO and an annealing process, the higher $E_{opt}$ of doped layers which lowered the effective barrier height at interfaces, and the reduced defect density by decreasing the RF power density during thin-film depositions.

The current conduction mechanism of DG TFLED’s had been briefly studied: the ohmic conduction dominated the carrier transport within the lower applied-voltage region, while the space-charge-limited current was the dominant current within the higher applied-voltage region where EL was observed. The estimated characteristic temperature $T_c$ of an $\alpha$-SiC:H equaled 2989 K at room temperature, which was much higher than that of undoped $\alpha$-Si:H and showed a higher trap-state density within the gap of $\varphi$-$\alpha$-SiC:H films. The $n$’s of fabricated TFLED’s were very close to 1, which revealed that the tail-to-tail-state recombination was dominant.

The simple fabrication process employed and the improved EL properties of the DG TFLED’s revealed would enhance the application potential of $\alpha$-SiC:H p-i-n TFLED’s significantly.

**ACKNOWLEDGMENT**

The authors are indebted to B. J. Liu, L. M. Tseng, Y. T. Juang, C. L. Tseng, and C. C. Shih for their enthusiastic
supports and encouragements. Also, thanks are given to J. Y. Chen, J. W. Pan, and S. L. Ning for their technical assistance and valuable discussion in this work.

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