Hydrogen passivation of visible $p$-$i$-$n$ type thin-film light-emitting diodes

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The effects of hydrogen passivation on the performance of visible $p$-$i$-$n$ thin-film light-emitting diodes (TFLEDs) have been investigated. The TFLEDs were fabricated using a photochemical vapor deposition method. The hydrogenation process was performed using an inductively coupled plasma system at a rf power of 800 W and a process pressure of 20 mTorr for 30 min. It was found that hydrogenation dramatically improved the performance of these TFLEDs. The threshold voltage was decreased by about 1 V, the electroluminescence (EL) peak shifted from 704.5 to 689 nm, the EL intensity increased by a factor of 3, and the brightness increased from 1 to 24 cd/m$^2$ by 24 times. © 1996 American Institute of Physics. [S0003-6951(96)02808-6]

In recent years, much attention has been paid to hydrogenated amorphous silicon carbide ($a$-SiC:H)-based $p$-$i$-$n$ thin-film light-emitting diodes (TFLEDs) due to their possibility of application to the flat panel display.$^1$ There was much progress in the performance of the TFLEDs, such as, brightness, threshold voltage, and wavelength of electroluminescence (EL) peak. Paasche et al.$^2$ introduced the hot-carrier tunneling injection layers to improve the efficiency of hole injection into the luminescent active $i$ layer. They obtained a brightness of 20 cd/m$^2$ at an injection current density of 1 A/cm$^2$. Recently, Jen et al.$^3$ reported an $a$-SiC:H $p$-$i$-$n$ TFLED with barrier layers at the $p/i$ interface, which showed a brightness of 342 cd/m$^2$ at an injection current density of 600 mA/cm$^2$.

In the case of a polycrystalline Si thin-film transistor (poly-Si TFT), hydrogen passivation has been widely used to decrease dangling bonds at grain boundaries as well as interface states in SiO$_2$/poly-Si interface.$^4$ As a result, the hydrogenated poly-Si TFT showed an improved performance.$^5$ This technique may be very useful to improve the performance of $a$-SiC:H TFLEDs. However, there was no report on the postgrowth hydrogenation of TFLEDs. We applied hydrogen passivation technique for the first time to $p$-$i$-$n$ type $a$-SiC:H-based TFLEDs using an inductively coupled plasma (ICP) apparatus that has not only high plasma density at a relatively low process pressure but also low plasma damage during the process.$^6$ In this letter, we report the effect of hydrogen passivation on the performance of visible $p$-$i$-$n$ TFLEDs such as threshold voltage, brightness, and EL spectrum.

Visible $p$-$i$-$n$ TFLEDs were fabricated on a tin–oxide ($SnO_2$)-coated glass substrate using the three-reaction chamber photo-CVD system shown in Fig. 1(a). All $p$-$i$-$n$ junctions were formed successively in vacuum so that all interfaces ($p/i$ and/or $i/n$ interfaces) could be kept from contamination. The diode has a structure of glass/SnO$_2$/p-$\mu$-Si:H/(2.3 eV)/i-$a$-SiC:H/(3.3 eV)/i-$a$-SiC:H/(3.0 eV)/n-$\mu$-Si:H/(2.4 eV)/Al and its vertical structure is shown in Fig. 1(b). An intrinsic $a$-SiC:H layer with a band gap of 3.0 eV was used as an important luminescent active layer and deposited by using the direct photo-CVD method from a gas mixture of Si$_2$H$_6$ and C$_2$H$_2$. $p$-$\mu$-Si:H and n-$\mu$-Si:H layers were used as hole and electron injectors into the luminescent active $i$ layer, respectively, and prepared by using the mercury-sensitized photo-CVD method from gas mixtures of SiH$_4$/H$_2$/B$_2$H$_6$ (6000 ppm) and SiH$_4$/H$_2$/PH$_3$ (2000 ppm), respectively. An intrinsic $a$-SiC:H layer 1.5 nm thick with a wide band gap of 3.3 eV was used to improve the efficiency of hole injection into the luminescent active $i$ layer. The thickness of $p$, $i$, and $n$ layers of fabricated TFLEDs was 15, 50, and 30 nm, respectively.

Figure 2 shows the schematic diagram of an ICP apparatus used for the hydrogen passivation process. The details...

FIG. 1. (a) A schematic diagram of three-chamber photo-CVD system with a load-lock chamber. (b). A schematic illustration of the structure of visible $p$-$i$-$n$ TFLED. Intrinsic $a$-SiC:H film of 50 nm thick with band gap of 3.0 eV was used as the important luminescent active layer. $p$-$\mu$-Si:H and n-$\mu$-Si:H layers were used as hole and electron injectors into the luminescent active $i$ layer, respectively. Intrinsic $a$-SiC:H layer of 1.5 nm with wide band gap of 3.3 eV was used to increase the efficiency of hole injection into the luminescent active $i$ layer.
of the ICP apparatus were given elsewhere. The hydrogen passivation process was performed under the following: rf power 800 W, pressure 20 mTorr, substrate temperature 300 K, substrate located at 8 cm below the quartz plate, and process time 30 min. Typical hydrogen passivation conditions are summarized in Table I.

Figure 3 shows the injection current density versus applied forward voltage characteristics of the TFLEDs without and with hydrogen passivation. As shown in Fig. 3, the threshold voltage was decreased by about 1 V. Figure 4 shows the brightness versus applied forward voltage characteristics of TFLEDs without and with hydrogen passivation. The brightness of visible TFLED was increased dramatically from 1 cd/m² to 24 cd/m² after hydrogen passivation. Figure 5 shows the EL spectra of TFLEDs without and with hydrogen passivation. The EL spectrum measurement was performed using a monochromator (Instrument S.A., HR. 640), a photomultiplier (Ataggo Bussan Co., No. 295), and a lock-in amplifier (Stanford Research Systems, SR510). It is observed that after hydrogen passivation, the EL spectrum intensity increases several times and the EL peak shifts towards shorter wavelength. EL peaks of TFLEDs without and with hydrogen passivation were observed at 704.5 and 689 nm, respectively. The increase of EL intensity as well as the shift of the EL peak towards shorter wavelength are believed to be due to a reduction of interface states at $p/i$ and $i/n$ interfaces by hydrogen passivation.

In summary, we fabricated visible $p-i-n$ TFLEDs using the photo-CVD technique, and investigated the effects of hydrogen passivation on the performance of TFLEDs. The hydrogen passivation process was performed using the ICP apparatus. We found that hydrogen passivation was a very effective method to improve the performance of TFLEDs. The hydrogenated TFLEDs showed a decrease of the threshold voltage by about 1 V, an increase of the brightness by 24 times, a shift of the EL peak towards shorter wavelength, and an increase of EL intensity. The observed results should en-

| Table I. Typical hydrogen passivation conditions of the ICP apparatus. |
|-----------------|-----------------|
| rf power        | 800 W           |
| Process pressure| 20 mTorr        |
| Process time    | 30 min          |
| Substrate temp. | 300 K           |

FIG. 2. A schematic diagram of ICP apparatus used to perform a hydrogenation process.

FIG. 3. The experimental injection current density vs applied forward voltage characteristics of visible $p-i-n$ TFLEDs without and with hydrogenation.

FIG. 4. The brightness vs applied forward voltage characteristics of visible $p-i-n$ TFLEDs without and with hydrogenation. The brightness was measured by using a photometer.

FIG. 5. The EL spectra of visible $p-i-n$ TFLEDs without and with hydrogenation. EL spectra were measured under 200 Hz square wave with peak-to-peak voltage, $V_{pp} = 7$ V and duty ratio of 10% using a monochromator (Instrument S.A., HR. 640), a photomultiplier (Ataggo Bussan Co., No. 295), and a lock-in amplifier (Stanford Research Systems, SR510).
encourage the application of the hydrogen passivation technique to visible TFLED fabrication.