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Visible Light a-SiC Multilayered Thin Film LED

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A new type of visible thin film light emitting diode made of multi-layered amorphous silicon carbide (a-SiC LED) has been developed. Employing with a-SiC/a-SiC superlattice as a luminescent active i-layer in the p-i-n junction, and p-i-n/p-i-n tandem configuration, the EL intensity has been increased by one order of magnitude as compared with a conventional single p-i-n cell. A series of systematic investigation on the performance improvement of a-SiC LED has been made.

1.Introduction

A visible light emitting diode made of amorphous silicon carbide (a-SiC LED) has been first developed by the authors's group in 1985¹⁻³. The device had the structure of glass/ITO/SnO_/p a-SiC(2.0eV)/i a-SiC(2.2-3.5eV)/ n a-SiC(2.0eV)/Al. p and n layers act as the injectors of holes and electrons into the luminescent active i-layer. It has been demonstrated that the emitting color can be controlled from red to green by choosing the optical band gap of the luminescent active i-layer. The brightness of orange emission was about 0.13 cd/m² with the forward injection current density of 200mA/cm² and a bias voltage less than 10 voltages. The a-SiC LEDs can be operated with a low voltage and have some significant advantages over the conventional crystal LEDs, such as wide area, ease of fabricating integrated type multi-color and tunable color LEDs, and low cost. However, the brightness obtained so far was still low for a practical application. In this work, for the purpose of putting it into a practical application, further efforts have been made on improving the emission efficiency by employing the p-i-n/p-i-n tandem and p-i(superlattice)-n structures. In the superlattice (a-SiC/a-SiC) i-layer, when holes and electrons are injected into the i-layer, these carriers are expected to be confined within the well layers sandwitched by the the barrier layers, resulting in the increase of luminescent efficiency. In this paper, we present the technical data on the material

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**Present Address: Shanghai University of Science and Technology, Shanghai, China. preparation, optimizations of device thicknesses and the LED characteristics. By utilizing these new structure, the EL intensity has been improved by one order of magnitude as compared with a conventional single p-i-n junction.

2.Sample Preparation

a-SiC films were prepared by the rf(13.56 MHz) glow discharge technique. The substrate temperature and gas pressure were 180°C and 1.0 torr, respectively. The optical band gaps of the a-SiC layers were changed by adjusting the gas a-SiC layers were changed by adjusting the gas flow ratio of silane(SiH₄) to hydrocarbon such as CH₄, C₂H₄ and C₂H₂ in the reaction gas. B₂H₆ and PH₃ were used as the dopant gases for p- and n-type injectors. The dark conductivity and the optical band gap of p-6 and n-type injectors were in the order of 10⁻⁶ (Ohm.cm)⁻¹ and 2.0 eV, respectively. The thickness of p- and n- layers are 150A and 300A, respectively. Glass/ITO/SnO₂ was used as the front transparent substrate. If was used as the front transparent substrate. It has been found that the a-SiC LEDs formed on a milky-rough ITO/SnO₂ exhibits an electroluminescent (EL) intensity about one order of magnitude larger than that formed on a smooth ITO/SnO_2 . After the formation of a-SiC ITO/SnO . After the lormatic layers, Al or Ag was evaporated on the top as a Details of the sample preparation have been described in the literature. As for a preliminary examination on the improvement of the EL intensity, in this paper we will focus on the orange emission LEDs, where the optical band gap of the luminescent i-layer is around 2.58-2.68 eV. In order to obtain abrupt interfaces in the multilayered structures, the glow discharge was turned off at each step of individual layer deposition and the reactor chamber was purged out by hydrogen gas for an appropriate time.

3.New Trials for improving the EL Intensity a.p-i-n/p-i-n Tandem Configuration

In a conventional single a-SiC p-i-n LED both the theoretical and experimental analyses have indicated that the EL intensity strongly



Fig.1 Schematic diagram of a-SiC multilayered p-i-n/p-i-n tandem LED(a) and its band diagram under forward biased condition (b).

depends on the i-layer thickness. In order to obtain a visible-light emission in a-SiC p-i-n LED, empirically the optical band gap of the i-layer has to be larger than 2.2 eV, for example 2.58-2.68 eV for orange emission. While the optical band gaps of the injector p- and nlayers are at most 2.0 eV due to the limit of the valency controllability. In this kind of devices, there exist the band discontinuities at the p/i and i/n interfaces. Therefore, holes and electrons are injected into the i-layer through inter-state tunneling from the p- and n- injector electrodes. It has been found in the previous studv that for an orange a-SiC LED (p(2.0eV) /i(2.58 eV)/n(2.0eV)) at a constant injected current the EL intensity becomes maximum when the thickness of the i-layer is as thin as 500 A. This might be due to the limited hole injection efficiency. However, in principle, a thicker luminescent layer will be desired for an increase in the EL intensity. One method to gain a thicker i-layer is to form the device having a p-i-n/p-i-n tandem configuration. From this view point, we have developed a new type of a-SiC LED constructed with the p-i-n/p-i-n tandem The schematic illustration of the structure. device structure is shown in Fig.l(a) and its suggested band diagram under forward bias condition is shown in Fig.1(b).

Fig.2 shows the relation between the EL intensity and injection current density J_{inj} measured at room temperature for the single cell and tandem cells. The cell area is 0.033 cm². pin(500A)/pin(500A) represents a tandem cell consisting of two pin cell of which each i-layer thickness=500A. As can be seen, the EL intensity of a tandem cell is larger than that of single



Fig.2 Relation between the EL intensity and injection current density for the orange emitting single and tandem cells. pin(500A)/pin(500A) represents a tandem cell consisting of two p-i-n cells of which each i-layer thickness=500A.



Fig.3 An example of orange emission pattern of a-SiC p-i-n/p-i-n tandem LED. The area of the emission pattern "tiger" is 10x15 mm². The injection current is about 10 mA.

cell by about one order of magnitude. These LEDs show orange emission and the EL spectra peaks around 1.9 eV. For reference, Fig.3 demonstrates an example of the orange emission pattern of a-SiC tandem LED formed on a glass/ITO/SnO₂ substrate. The tiger pattern has a size of 10x15 mm². The injection current was 10 mA with the forward voltage = 13 voltages. The emission pattern was achieved by etching the front-side transparent ITO/SnO₂ electrode. The luminescent efficiency was estimated to be the order of 10 -10 It should be noted here that with this kind of tandem LEDs, not only the EL intensity is increased, but a tunable or multicolor LED can also be easily fabricated on a same substrate by designing the different optical band gaps of the i-layers.







Fig.4 Device structure of a-SiC p-i-n LED, where the luminescent i-layer is a-SiC/a-SiC superlattice(a) and its band diagram under forward biased condition(b).

b.a-SiC/a-SiC Superlattice Luminescent Layer

Another trial to increase the EL intensity to apply a-SiC/a-SiC superlattice as a luminescent i-layer in the p-i-n junction. There have already been various reports on the increase of photoluminescent intensity in amorphous superlattice such as a-Si/a-SiC⁴, a-Si/a-SiN⁵ superlattice such as a-Si/a-SiC The increase of PL intensity and the systems. blue shift of the PL spectra have been considered to be due to the carrier confinement and quantum size effects. One of the full utilization of these effects might be a light emitting device. However, no application of amorphous superlattice to a light emitting device has yet been reported In this paper, we report the application so far. of a-SiC/a-SiC superlattice in the actual a-SiC LEDS for the first time. a-SiC/a-SiC superlattice is constructed of the alternating layers of wide gap a-SiC (barrier layer) and narrow gap a-SiC (well layer). Fig.4(a) shows a schematic illustration of the p-i(superlattice)-n LED and Fig.4(b) shows its band diagram for the forward-biased condition. When holes and electrons are injected into this i-layer, these carriers will be confined within the well layers sandwitched by the barrier layers resulting in the increase of luminescent efficiency. In this work the optical band gaps of a barrier and a well were set to be 2.58 eV and 2.68 eV, From the results of the respectively. photoemission measurement, the conduction band discontinuity (ΔE) and the valence band discontinuity (ΔE) has been evaluated to be about 0.025 eV and 0.075 eV, respectively.



Fig.5 EL spectra measured at room temperature for a-SiC LEDs, where the i-layers are a-SiC(well:E =2.58eV)/a-SiC(barrier:E = 2.68eV) superlattice. For comparison, the EL spectra for the conventional LEDs consisting of a single i-layer are also shown.

Fig.5 shows the EL spectra measured at room temperature for p-i(superlattice)-n LEDs and conventional p-i-n LEDs. The combinations of the thicknesses of a well layer/a barrier layer shown in the figure are 40/50A and 50/50A. The total of the i-layer thickness is 500A. As compared with the cell of which the i-layer is made of only the well material, the EL spectra for the superlattice samples lightly shift toward shorter wavelength. The magnitude of the EL intensity for the superlattice LEDs are also larger than those of conventional single LEDs. These results are considered to be due to the quantum size and confinement effects in the carrier the As can be seen in Fig.5, in a superlattices. superlattice structure, the thicknesses of a well and a barrier are very important for an effective carrier confinement. From this view point, we have conducted a systematic investigation on the dependence of the EL intensity on the thicknesses and of barriers in the wells actual p-i(superlattice)-n LEDs. Fig.6 summarizes the dependence of EL intensity on the well thickness, where the thickness of a barrier is kept constant at 50A. The repetition number was changed so as to achieve the total thickness of the i-layer=500 or 1000A. For comparison, the EL intensities of normal p-i-n junctions (without superlattice), of which the optical band gaps are equal to those of the well and barrier are also shown. The EL intensity becomes maximum when the well layer thickness is around 50A. The optimal condition of the barrier thickness has also been examined and the results are shown in Fig.7. The EL



Fig.6 Dependences of the EL intensity on the well thickness. The barrier thickness=50A. The total i-layer thickness=500,1000A.

intensity has its peak when the barrier thickness is around 100A. By optimizing the well and barrier thicknesses, the EL intensity is increased by the factor of 3-5 as compared with a conventional p-i-n cell. However, the increase of the EL intensity in a-SiC p-i(superlattice)-n LED is relatively smaller than the results of photoluminescence in superlattice alloys 5-7). This might be due to the difference in the carrier excitation process. In the PL process, the amount of holes and electrons are equally excited optically by an exciting light. While, in a-SiC LED, the electroluminescence comes from the radiative recombination of holes and electrons electrically injected from p- and nelectrodes. As described in section3. the barrier height at the p/i and i/n interfaces limit the the injection efficiency of these carriers, especially for holes because of the ΔE > ΔE . In order to increase the hole injection efficiency we do need a new technology In order to increase the hole for achieving a wider optical band gap of the pand n- type a-SiC.

5.Conclusion

The new efforts have been made to improve the EL intensity in a-SiC LEDs. By employing a-SiC/a-SiC superlattice as a luminescent active i-layer and p-i-n/p-i-n tandem configuration, the orange EL intensity has been increased by one of magnitude as compared order with a conventional single p-i-n cell. It has also been suggested that with the strucutre of p-i-n/p-i-n, a tunable and/or multicolor LED can be directly fabricated on a same substrate by adjusting the optical band gaps of each i-layer. This work has shown that a-SiC LED would become a new candidate device for a low-cost, low-voltage, wide-area, flat-panel display.



Fig.7 Dependences of the EL intensity on the barrier thickness. The well thickness=50A. The total i-layer thickness=500,1000A.

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