

Cathodo-Electro-Luminescence of Diamond p-i-p Layered Structure

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P-i-p tri-layered light emitting diamond diodes (LEDDs) have been fabricated by selective homoepitaxy for the first time. The properties of the EL were investigated by comparing with that of the CL from the p-i-p structures and found to be different from those of the CL. The enhancement of CL intensity was observed by simultaneous application of electron beam and electric field to the specimens. In the structures, the results intimated that the EL emission occurred at around reversely biased diamond p-i junction.

1. INTRODUCTION

Excellent physical properties of diamond, such as wide energy band-gap (5.5 eV) and high breakdown field (10^6 - 10^7 Vcm⁻¹), promise to realize high-power and high-energy optical emission devices for future optoelectronic applications. Actually, light emission from diamond was observed in the short wavelength range from blue to ultraviolet. The investigation of diamond optical emission properties have been mainly made by using cathodoluminescence (CL). Electroluminescence (EL) of diamond has also been reported by several laboratories but their reports are only preliminary or superficial one. Thus, to date there has been no report on fabrication of the light emitting device structures based on layered homoepitaxial diamond. Furthermore, even the emission mechanism itself is not clear.

In the present work, we have fabricated p-i-p tri-layered light emitting diamond diodes (LEDDs) for the first time. We have compared the properties of the EL with that of the CL from the structures. By investigation of interaction between EL and CL we closely examined the emission mechanism of the LEDDs.

2. EXPERIMENTAL

The LEDDs were fabricated by the selective homoepitaxy¹⁾ employing the electron-cyclotron resonance (ECR) microwave plasma-assisted chemical vapor deposition (CVD) with (CO, B₂H₆)/H₂ gaseous source. First, boron-doped (B/C=800 ppm) diamond film (p-layer) was simply deposited on an entire (100) synthetic-diamond single-crystal substrate. Then, an undoped diamond film (i-layer) and a boron-doped (B/C=800 ppm) diamond film (p-layer) were selectively grown successively on the preceding layer using the selective epitaxy technique with a yttria-

stabilized zirconia thin-film mask²⁾. Each layer was grown to about 1 μm.

After the preparation of the films, specimens were annealed in oxygen ambient (0.2 Torr, 500°C, 20 min) to remove the surface conduction caused by the hydrogen plasma³⁾. Pt/Ti electrodes were deposited on the p-layers by electron beam evaporation with subsequent annealing at 500°C for 30 min in vacuum to form ohmic contacts. For electrical measurement, Au wire was bonded to the electrodes with In metal.

Specimens were subjected to the pulsed bias of 5~10 % duty ratio and 25 Hz frequency to avoid Joule heating of the specimens during the EL measurement. CL measurement was also performed to compare and investigate interaction with EL. For the investigation on temperature dependence of the luminescence, measurement temperature are decreased from room temperature to ~80 K.

3. RESULTS AND DISCUSSION

Figure 1 shows the structure of the p-i-p LEDD. An scanning electron microscopy (SEM) image of the LEDD is shown in Fig. 2, where the patterned area which appears black corresponds to selectively grown undoped diamond layer (i-diamond), and the narrow square patterned area which appears white corresponds to selectively grown boron-doped diamond layer (p-diamond).

Advantages of the selectively grown homoepitaxial diamond layered structures used here are to be capable of applying sufficient bias electric field (up to 3×10^6 V/cm) to the i-diamond layer and to be fully isolated the top p-diamond layer from the bottom p-diamond layer. These advantages make it possible to evaluate true value of diamond properties by reducing any leakage current.

The observed spectrum of the EL from the p-i-p tri-layered LEDD is shown in Fig. 3 where the device is

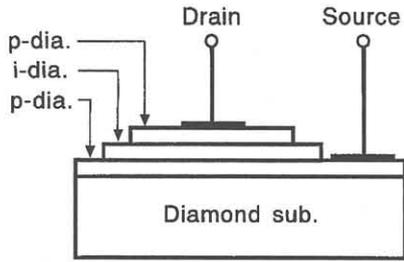


Fig. 1. Configuration of p-i-p tri-layered LEDD

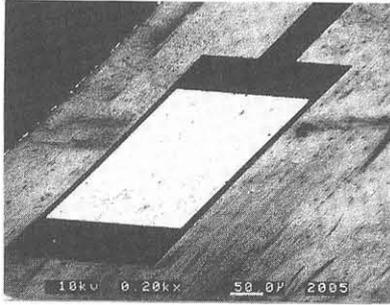


Fig. 2. SEM image of p-i-p tri-layered structure

applied by pulse bias voltage V_B of 300 V. The spectrum of the EL shows peak at ~ 550 nm. The relation between EL intensity and the bias voltage was in proportion to the diode current: the EL intensity rapidly increased when the bias voltage was in excess of about 100 V (Fig. 4.).

For reference, the typical CL spectrum (accelerating voltage of 13 kV) from the boron doped diamond layer is also shown in Fig. 3. Although comparing these two spectra, the spectrum of the EL seems to be quite similar in shape to that of the CL from the boron doped diamond layer, we measured the temperature dependence of their luminescence intensities in order to examine the emission processes of the EL and the CL. Since it does not necessarily follow that these origins are the same because of only the similarity in shape of their spectra.

The results of the measurements are shown in Fig. 5. The intensity of EL has been increased at higher temperatures and saturated around 200 K, as shown in Fig. 5 (a). This is explained qualitatively in the following way. Since the observed EL intensity is in proportion to the current on the whole, the excitation efficiency increases with temperature. Therefore the EL intensity increases as temperature increases if the luminescence efficiency remains unchanged or slightly changed with temperature. Whereas at higher than 200 K, the observed EL intensity saturates and begins to decrease. The saturation of the EL intensity around 200 K signifies decreasing in luminescence

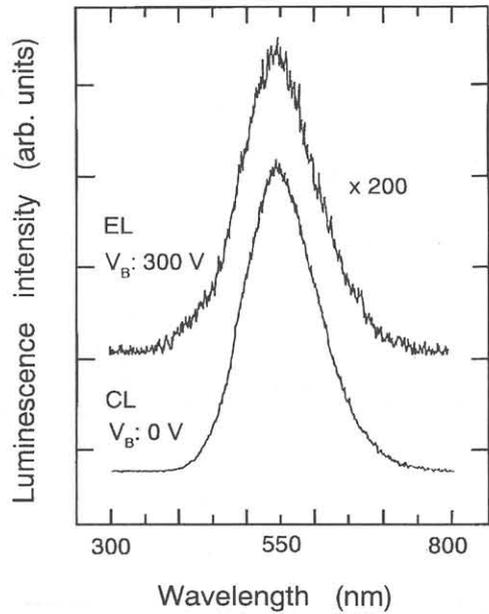


Fig. 3. Spectra of EL and CL from p-i-p tri-layered LEDD

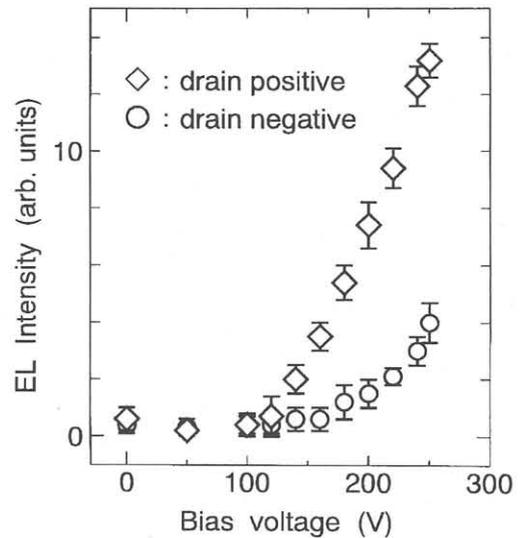


Fig. 4. EL intensity vs bias voltage characteristics of p-i-p tri-layered LEDD

efficiency possibly caused by thermal quenching through non-radiative transition processes.

On the other hand, the temperature dependence of the CL intensity does not represent particular tendency in change in this temperature range, as shown in Fig. 5 (b). Consequently this difference of the temperature dependencies of the luminescence intensity signifies that the emission process of the EL is not the same as that of

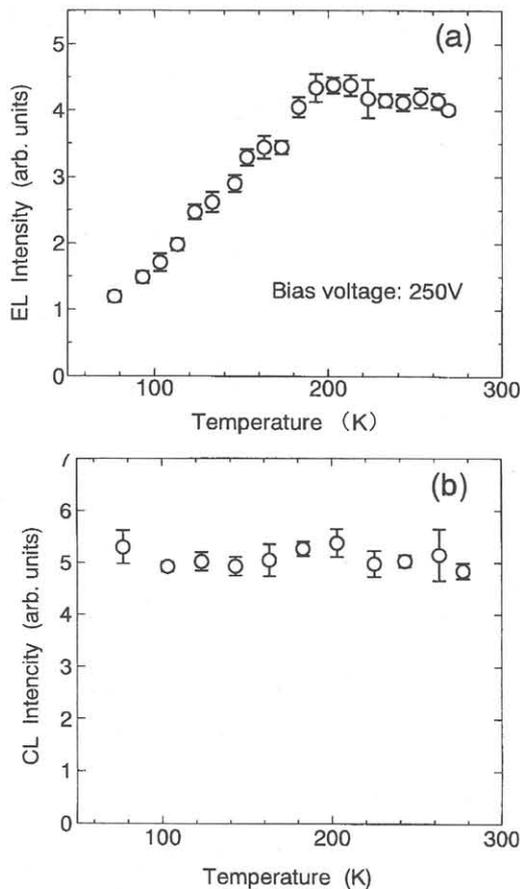


Fig. 5. Variation of EL(a) and CL(b) intensities from p-i-p tri-layered LEDD with temperature

the CL from the boron doped diamond layer.

Here, we turn closely our attention to the bias polarity dependence of the EL intensity in Fig. 4. In this figure, we can see the difference in the EL intensity (bias polarity: the intensity where the drain was positively biased to the source) was higher than the opposite case. This fact intimated that the optical process involved high field effect and the changing bias polarity altered the light emitted position To investigate the excitation mechanism of the diamond EL, we examined the interaction between EL and CL: applying the bias voltage to the LEDD under excitation by electron beam with a certain accelerated voltage, the luminescence behaved in a distinctive way. Although data are not given here, we observed enhanced amount of CL intensity (accelerating voltage of 13 kV) with application of the bias voltage. It is worth noting here that the enhanced amount of CL intensity with the bias voltage of 250 V is much larger than the amount of the EL intensity excited separately by the corresponding bias voltage. In this case, the CL and the EL effects reinforce each other.

For further investigation, by changing the accelerating

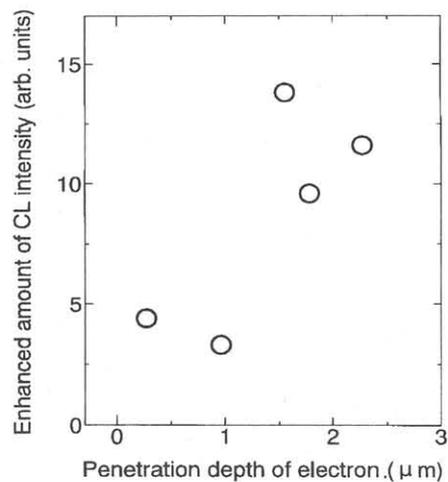


Fig. 6. Relationship between enhanced amount of CL intensity and penetration depth of electron

voltage of electron beam, we examined the depth profile of the enhanced amount of CL intensity with application of bias voltage (250 V), as shown in Fig. 6. In this figure, asymmetric profile of the CL inside i-diamond layer can be seen. This results and the bias polarity dependence of EL intensity confirmed that the excitation of EL occurred from reversely biased diamond p-i junction in this structure.

4. CONCLUSIONS

We fabricated p-i-p tri-layered LEDDs by the selective homoepitaxy. The spectrum of the EL was quite similar in shape to that of the CL from the boron doped diamond layer but these origins are not the same. We examined the effect of the applied electric field on CL properties. With a certain accelerating voltage for CL, EL and CL effects reinforced each other. We confirmed that the optical process can be expressed in terms of the combination of the injection and high field effect, and the excitation of EL occurred from reversely biased diamond p-i junction in this structure.

5. REFERENCES

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