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Images and Energy Distributions of Electrons Emitted from a Diamond pn-Junction Diode

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1. Introduction

Diamond pn-junction diodes with negative electron affinity (NEA) surfaces on the p-electrodes are expected to be good electron emitters. Recently, Koizumi et al. [1] fabricated a diamond pn-junction diode that showed an evidence of electron emission under a forward diode voltage with an electron emission efficiency (ε) to diode current of ~$2x10^{-4}$. The diamond pn-junction diodes were further improved to have better ε's [2] and the one used in this work showed ε to be ~10^{-2} under a forward diode current of several tens μA. In this study, the evidence and feature of electron emission have been shown by observing electron emission images and electron energy distribution curves from the diamond pn-junction diode by an electron emission spectro-microscope.

2. Experimental

The pn-junction diode used in this study was made on a HPHT Ib single crystal diamond {111} substrate (2x2x0.5 mm^3). Phosphorous doped (~$1x10^{19}$ cm^{-3}), n-type diamond was first grown for a thickness of 5~10 μm and then boron-doped (~$1x10^{18}$ cm^{-3}), p-type diamond was grown for a thickness of ~0.5-1 μm by MW plasma CVD methods. A circular (250 μm in diameter, ~1 μm in height) diamond pn-junction mesa was created by a RIE method and a circular (150 μm in diameter) ohmic metal (Au/Ti) contact was made on the mesa (p-type diamond surface). Au lead wire (25 μm diam.) was bonded to the metal contact and connected to an electrode of a sample holder. The n-type diamond was electrically connected by a thin Mo plate to the second electrode of the sample holder. The sample was then installed to a UHV (~$5x10^{-11}$ Torr) electron emission spectro-microscope (Omicron IS-PEEM). Good pn-diode characteristics (~10^8 at ±20 V) were observed *in-situ* in the UHV apparatus.

The electron emission spectro-microscope was composed of electro-static-lens optics together with an electron energy-analyzer. A micro-spot electron energy analysis of emission electrons was

possible at a spatial resolution of 1 μm in diameter using an iris aperture placed on the first image plane. Spatial resolution as an emission microscope was ~20 nm. For photoemission electron microscope, a Xe-discharge lamp was used whose highest photon energy exceeds 6.2 eV. All the measurements were performed at the sample temperature of ~200 °C.

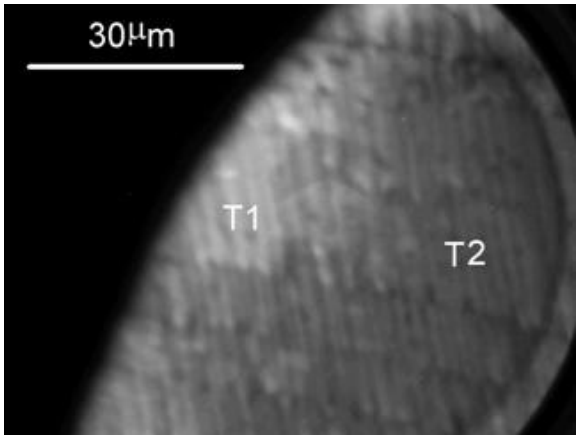

Fig.1 Emission image from the mesa p-electrode of the diamond pn-junction diode at a diode current of 40 μA.

3. Results and discussion

Figure 1 shows an emission image of the circular p-type diamond mesa (p-electrode) at a forward diode current (I_d) of 40 μA at a forward diode voltage (V_d) of 29.3 V. The facetted structure of mesa terrace can be seen in Fig.1. By comparison of Fig.1 with a Nomarski microscopic image, it was found that the emission edge coincides to the edge of mesa. Thus, Fig.1 proves that electron emission indeed occurs at the terrace of p-electrode. Energy distribution curves (EDC's) of emitted electrons at two places (as marked T1, T2 in Fig.1) were measured by placing the iris aperture and using the electron energy analyzer.

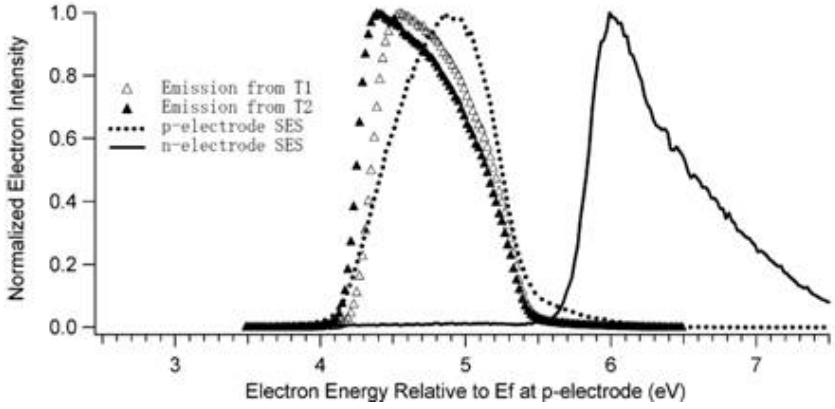

Fig.2 EDC's of electrons emitted by forward diode voltage at two places (T1, T2) in Fig.1 together with EDC's of secondary electrons excited by Xe-lamp at p and n-electrodes.

The resulting EDC's are shown in Fig.2 together with Xe-lamp induced secondary electron spectrum (SES) from the p-electrode and from the n-electrode near the p-electrode. A bias voltage of -3.0 V was supplied to the p-electrode in order to analyze electrons at low energy cutoff. The SES spectrum from the p-electrode was measured at V_d=0.0 V and the SES from the n-electrode was measured at $I_d = 40$ μA and $V_d = 24.1$ V.

Figure 2 shows that the low-energy cutoff of emitted electrons from T1 and T2 coincides with that of SES from p-electrode. This proves that electrons at the pn-junction are injected to the conduction band of p-electrode and transferred to the surface. The low-energy cutoff position is dependent on the electron affinity at the surface. It is generally true that the hydrogen-terminated CVD p-type diamond surfaces have negative electron affinity. Thus, the low-energy cutoff would coincide with the lowest un-occupied states at the p-electrode surface.

In Fig.2, the low-energy cutoff of SES spectrum of electrons from n-electrode under V_d=24.1 V lies at about 1.5 eV above the low-energy cutoff from p-electrode. The electron affinity at the present hydrogen-terminated n-electrode surface may be negative. However, the low-energy cutoff of n-electrode as seen in Fig.2 is not at the junction but at the surface. The Fermi level position at the n-type diamond is expected to be different from that in the bulk [3]. Thus, direct comparison of cutoff energies between p- and n-electrodes may not be meaningful.

4. Conclusions

A diamond pn-junction diode with an electron emission efficiency to diode current of ~10^{-2} was examined by an electron emission spectro-microscope. The evidence that electron emission indeed occurs at the terrace of p-electrode was obtained. The features of energy distribution curves for emitted electrons showed that electrons at the pn-junction are injected to the conduction band of p-electrode and transferred to the p-electrode surface.

References

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