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Fabrication of bipolar junction transistor on (001)-oriented diamond by utilizing phosphorus-doped *n*-type diamond base ☆

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ABSTRACT

Bipolar junction transistors (BJTs) with vertical *p*–*n*–*p* structure were fabricated on (001)-oriented diamond by utilizing phosphorus-doped diamond for the base *n*-type layer, and the electrical properties were examined, including the diffusion length of injected holes. The basic transistor action with stable current response from 100 nA to 50 μA was clearly observed at room temperature in both common-base and common-emitter configurations. Heavily phosphorus-doped diamond was introduced by the selective doping method under the base electrodes in order to reduce the series resistance, which is essential for realizing BJTs on (001).

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1. Introduction

For a long time, it had been considered that diamond was an insulating material because of the difficulty of controlling its conductivity by impurity doping. This understanding has changed drastically in recent years [1–4]. Boron and phosphorus atoms have been demonstrated to be effective dopants for diamonds, stimulating much research on diamond junction applications. Schottky barrier diodes (SBDs) based on diamond have shown high blocking voltage up to 10 kV [5] and high thermal stability up to 400 °C. Fast switching properties with low on-resistance of around 0.3 mΩ cm^2 and high breakdown field of around 3.4 MV/cm have been reported in Schottky-pn diodes [6]. High frequency field effect transistors (FETs) have also been established by using a hydrogen-terminated surface conductive layer, with a maximum frequency of more than 45 GHz at RT, as well as III–V compounds [7]. Junction field effect transistors (JFETs) were also fabricated by selective growth of phosphorus-doped n^+-type diamond [8]. The JFET showed a very low leakage current of the order of 10^{-15} A and steep subthreshold swings of 95–120 mV/decade. Moreover, an AlN/diamond heterojunction FET with p-channel and normally-on depletion mode has been developed on oxygen-terminated (111) diamond substrate by metal–organic vapor phase epitaxy [9,10]. A metal–oxide–semiconductor device based on Al_2O_3 has also been developed with attractive properties, in which the inversion layer was observed by capacitance measurements [11]. Such devices exploit the high mobility, breakdown, and power handling properties of diamond. These characteristics may lead to individual power devices capable of switching voltages of many tens of kV and kA for future electronics.

The bipolar junction transistor (BJT) is also one of the major power switching devices. BJTs based on diamond may offer benefits in high-power applications, including potentially lower on-resistance from conductivity modulation due to minority carrier injection, the absence of a gate insulator, and hydrogen-terminated surface conductivity. Recently, we have demonstrated a diamond BJT with a current gain of around 10 at room temperature by utilizing optimized device geometry in (111)-oriented diamond [12]. This observation of current gain properties in diamond BJT is a major breakthrough that brings diamond closer to high-power switching applications. In this study, we fabricated and characterized diamond BJTs on (001)-oriented diamond with vertical type *p*–*n*–*p* structure, and examined the diffusion length of injected holes in the base *n*-type layer compared to the previous (111) BJT.

2. Experimental procedures

Intrinsic, boron-, and phosphorus-doped diamond films were grown using microwave plasma enhanced chemical vapor deposition (CVD) with source gasses of hydrogen (purity: 9 N), methane (6 N), diborane for *p*-type doping, and phosphine for *n*-type doping. The growth conditions for each semiconducting layer are summarized in Table 1. The substrate used was HTHP IIb-type diamond with boron concentration of 6×10^{19} cm^{-3}, which shows *p*-type semiconducting properties with resistivity of ~3 Ω cm at room temperature by four

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probe method. The misorientation angle was around 2° from the (001) surface, measured by X-ray diffraction.

The substrate was repolished to remove the mechanical polishing patterns, which are usually observed by optical microscope/Nomarski prism, and then cleaned by the following chemical treatments. First, the substrate was boiled in an acid mixture ($H_2SO_4/H_2O_2/H_2O$, 3:1:1) at 220 °C for 15 min to remove organic and metallic surface contamination, followed by HF treatment for 5 min to remove SiO_2 and metallic contamination, and then the substrate was boiled again in SCl ($NH_4OH/H_2O_2/H_2O$, 1:1:5) at 75 °C for 15 min to remove the organic contamination.

The surface morphology of the grown diamond was observed using a differential interference microscope with a Nomarski prism. The incorporation of impurity atoms was evaluated using secondary ion mass spectroscopy (SIMS). Cs^+ accelerated at 14.5 keV was used as the primary ions, and the impurity density of phosphorus, hydrogen, nitrogen, and boron atoms was quantified using implanted standard samples.

The patterned electrodes were fabricated by conventional electron-beam lithography, metallization, and the lift-off process. As-grown diamond films were treated with an acid mixture (H_2SO_4/HNO_3, 3:1) at 220 °C for 30 min. Ti (50 nm)/Pt (50 nm)/Au (150 nm) contacts were deposited on the diamond by electron-beam evaporation followed by thermal annealing in Ar atmosphere at 420 °C for 30 min. The DC output properties of the diamond BJT were measured at room temperature using high-resolution source-measure unit (HRSMU) modules of the Agilent B1500A semiconductor device analyzer.

3. Results and discussion

Fig. 1 is a whole optical image of the diamond BJTs fabricated in this study. The vertical *p–n–p* junction structure was fabricated on IIb-type (001)-oriented substrate. Each layer was grown in different CVD reactors in order to suppress cross contamination of boron and phosphorus impurities. The magnified image of one diamond BJT and a schematic diagram of selectively grown n^+ contacts are shown in Fig. 1(b). The backside collector electrodes are common in all devices. The finger-type electrodes are accepted in the emitter and base electrodes, and the gap between the emitter and base electrodes is 1 μm. Prior to the metallization process, the entire surface was treated with an acid mixture in order to create an oxygen-terminated surface for device isolation and surface passivation.

The depth profiles of boron and phosphorus impurities are summarized in Fig. 2. The boron concentration in the emitter layer was controlled at 1×10^{21} cm^{-3} with a thickness of 250 nm, and the phosphorus concentration in the base layer was controlled at 1×10^{18} cm^{-3} with a thickness of 600 nm. The intrinsic layer with impurity concentration of less than 1×10^{15} cm^{-3} was introduced between the base–collector junctions in order to suppress leakage current and increase the blocking voltage. The boron and phosphorus atoms are incorporated as arranged and no cross contamination can be found. The heavily phosphorus-doped n^+ layer with the expected concentration of 1×10^{20} cm^{-3} was selectively introduced in the

Table 1
Typical growth conditions for each *p*, *i*, and *n* layers for BJT. Each layer was grown on each different CVD reactor to suppress the cross contamination of boron and phosphorus impurities.

	p^+ emitter	*Intrinsic* layer	*n* base	n^+ contact
Source gasses	H_2, CH_4, B_2H_6	H_2, CH_4, O_2	H_2, CH_4, PH_3	H_2, CH_4, PH_3
Temperature [°C]	850	850	900	900
CH_4/H_2 [%]	0.6	4.0	0.4	0.05
(Impurity gas)/CH_4 [%]	1.0	2.5	5.0	50
Pressure [torr]	50	170	25	75
MW. power [W]	1200	4200	750	750

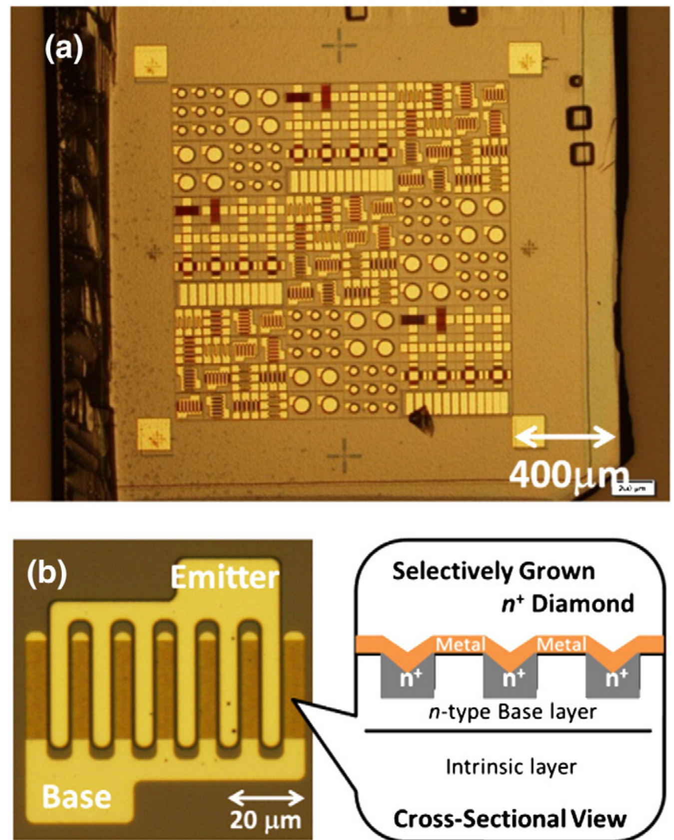

Fig. 1. (a) Optical microscope image of the fabricated diamond BJTs on IIb-type boron-doped (001) substrate. (b) Magnified image of finger-type electrode with selectively grown n^+ diamond.

n-type base contact region by the selective doping method [13]. The initial trench structure for the selective growth method was 300 nm deep and 500 nm wide as shown in Fig. 1(b).

Fig. 3(a) shows the current–voltage (*I–V*) properties obtained for the emitter–base diode with and without the selectively grown n^+ diamond in base *n*-type contact. The introduction of n^+ diamond improves the *I–V* curves with higher forward current and lower turn-on voltage around 4.5 V. A clear rectification property with the low leakage current level maintained at around 0.1 nA up to −100 V is also obtained in the base–collector diode as shown in Fig. 3(b). The

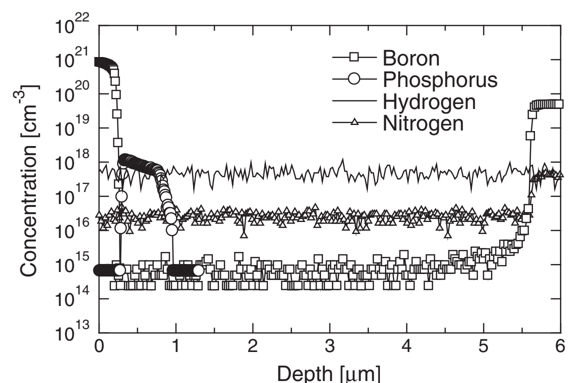

Fig. 2. SIMS depth profile obtained for the diamond BJT. The boron concentration in the emitter layer is 1×10^{21} cm^{-3} with thickness of 250 nm, and the phosphorus concentration in the base layer is 1×10^{18} cm^{-3} with 600 nm. Hydrogen and nitrogen are under the background level of SIMS measurements.

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