

Electron sources based on diamond pin-diodes

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Abstract— Efficient electron sources are of ongoing interest in particular for high power terrestrial and space telecommunications and radar applications. With conventional cathode technology based on thermionic- and field electron emission a novel approach for direct electron emission is realized through a diamond pin diode. Electrons injected into the conduction band of the intrinsic layer of the diode can be released into vacuum with a negative electron affinity surface of the i-layer. The diamond pin diodes were prepared on boron doped (p-type) substrates with (111) surface orientation. A high purity intrinsic and a phosphorus doped diamond layer (n-type, ~400nm thickness) were deposited in dedicated PECVD systems, respectively. An additional contact layer comprised of nanostructured carbon was grown in a dedicated PECVD. The layered device was processed by lithography utilizing an aluminum hard mask to etch mesa structures with diameters ranging from 50 μm to 200 μm . The final devices were treated in a pure hydrogen plasma to induce the negative electron affinity properties of the i-layer. After an annealing step in high vacuum individual pin diodes were biased in forward current and voltages up to 20V. The observation of light from the diode was attributed to the UV exciton state and indicated bipolar transport. At a diode current of about 80mA an electron emission current of 25 μA was observed from a single 200 μm diameter diode.

Keywords— *Diamond, plasma-enhanced chemical vapor deposition, doping, phosphorus, single crystal, nanostructured carbon, electron emission, pin diode, solid state electronics.*

I. INTRODUCTION

Electron sources are widely utilized in terrestrial and space telecommunications through travelling wave tubes (TWTs), radar, free electron lasers (FEL) and electron probing techniques in general [1, 2].

With ongoing research into diamond for power electronics and energy conversion applications the materials' conventional electron emission capability through thermionic- and field emission was extended when electron emission was observed from a diamond pn junction diode [3, 4, 5]. Diamond as a wide band-gap semiconductor presents a set of unique materials properties that suggest its application in power electronics. The ability of its lattice to incorporate acceptors (boron) and donors (nitrogen, phosphorus) (Fig. 1. (a)) presents a means to engineer semiconductor pn-junction for solid state devices. Furthermore, the ability of its surfaces to attain a negative electron affinity (NEA) characteristics was

exploited in electron emission research.

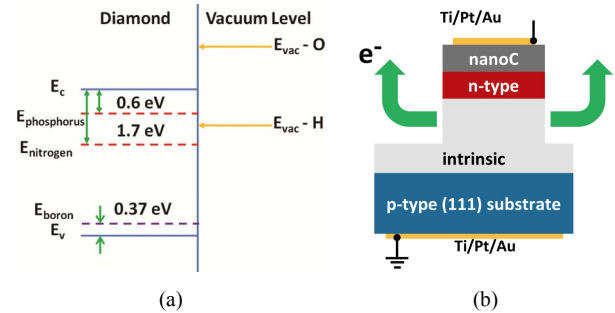


Fig. 1. Schematic band diagram of diamond with impurity levels of boron (acceptor), nitrogen and phosphorus (donor) and negative electron affinity surface under hydrogen termination ($E_{vac}-H$); conduction band and valence band levels are indicated by E_c and E_v , respectively (a) and a schematic of the pin emission diode using a nanostructured carbon (nanoC) contact layer (b).

We present a novel approach for electron emission utilizing a diamond pin-diode schematized in Fig.1. (b). The structure was grown by plasma-enhanced chemical vapor deposition (PECVD) and processed by photo-lithography.

II. EXPERIMENTAL

A. Plasma-Enhanced CVD Growth

The diamond pin diodes were prepared on commercially obtained high-pressure, high-temperature (HTHP) type IIb substrates with (111) surface orientation. The 3mm x 3mm x 0.3mm plates were wet-chemically cleaned and an intrinsic diamond layer was deposited in a dedicated CVD reactor. The successive, n-type, phosphorus doped diamond layer was grown in a dedicated CVD reactor utilizing a 200gas mixture of ppm trimethylphosphine (TMP) in hydrogen as the dopant source. A final contact layer, nitrogen incorporated nanostructured carbon, was grown under argon addition in a dedicated CVD reactor.

B. Device Processing through Lithography

Photo-lithography was employed to fabricate the diamond pin diodes with circular mesa structures of varying diameter, typically 50-200 μm . An aluminum hard mask was employed to plasma etch the diamond layers using O_2/SF_6 chemistry. Electrical contacts were deposited using Ti/Pt/Au metallurgy.

The final diode structure (Fig. 1. (b)) was then exposed to a pure hydrogen plasma at ~850 $^{\circ}\text{C}$ to establish NEA surface properties.

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III. ELECTRICAL CHARACTERIZATION

A. Nanostructured Carbon Contact Layer

The nitrogen incorporated nano-structured carbon layer was characterized in high vacuum using a 2-point probe setup utilizing gold electrodes with a $10\mu\text{m}$ tip diameter. The contacts were separated by 0.75mm and I/V measurements were obtained at temperatures up to 500°C . Fig. 2. (a) indicates the ohmic nature of the resistivity where at a bias of 1V a significant current of $\sim 4.5\text{mA}$ was measured. The current was observed to increase with temperature indicative of n-type conduction. With the preferential incorporation of nitrogen into the high density graphitic grain boundaries defect states from π bonds and threefold-coordinated carbon atoms (C3np) establish bands below the Fermi level shown in Fig.2. (b) that can contribute to the electron transport.

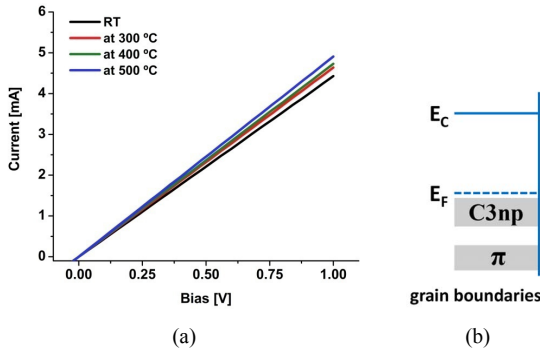


Fig. 2. I/V characterization of a nano-structured carbon layer using gold probes separated by $\sim 0.75\text{mm}$. (a) Defect states in the grain boundaries establishing bands below the Fermi level, E_f . The conduction band is indicated by E_c .

The same nano-structure carbon layer (nanoC) was deposited on the n-layer of the pin-diamond diode structure to evaluate its effects on diode and emission properties.

B. Electron Emission from pin-(nanoC) diamond diodes

Prior to electron emission characterization the pin-diode sample was annealed at $\sim 650^\circ\text{C}$ in a high vacuum ambient. Individual diodes were contacted by a Au probe and a forward current applied. Simultaneously, the anode, positioned near the mesa, was biased at 300V to collect electrons emitted from the device.

Operating the diodes under forward bias resulted in light emission attributed to the UV exciton and was indicative of bipolar transport (Fig. 3. (a)). Electron emission from $200\mu\text{m}$ diameter pin diamond diodes with an i-layer thickness of $1\mu\text{m}$ and $0.5\mu\text{m}$ was observed as shown in Fig. 3. (b) with an emission current exceeding $5\mu\text{A}$ at 400mA diode current and under a bias of $\sim 20\text{V}$. No significant effect of the i-layer thickness to the emission current was observed for thinner i-layer devices.

With the insertion of a nano-structured carbon contact layer electron emission from the pin-nanoC diode was significantly enhanced to $\sim 25\mu\text{A}$ at a diode current of 80mA . This increase of the electron emission was attributed to

improved electron injection into the device under a reduced diode forward bias of $\sim 16\text{V}$.

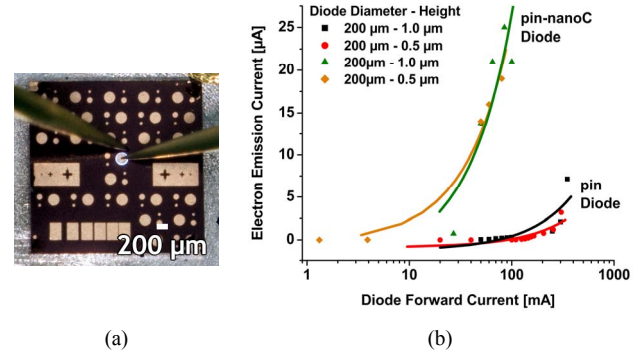


Fig. 3. Diamond pin-diode in forward bias exhibiting light emission indicative of bipolar transport. (a) Electron emission current for $200\mu\text{m}$ diameter pin diamond diodes with an i-layer thickness of $1\mu\text{m}$ and $0.5\mu\text{m}$. Diamond diodes with a nano-structured carbon contact layer (pin-nanoC) exhibit a significant improvement in the emission current (orange/green data). (b)

Secondary ion mass spectroscopy (SIMS) of the same pin-nanoC device shown in Fig. 4. (b) communicated a phosphorus concentration in the n-layer of $\sim 2.3 \times 10^{19} \text{cm}^{-3}$. For the 220nm thick nano-structured carbon layer a nitrogen incorporation of $\sim 3.3 \times 10^{20} \text{cm}^{-3}$ was measured.

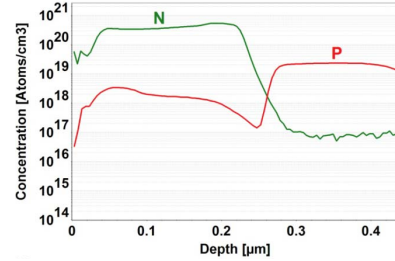


Fig. 4. Secondary ion mass spectroscopy of a pin-nanoC diode communicating high nitrogen incorporation for the nanostructured carbon contact layer.

These results indicated the ability of the highly nitrogen doped nano-structured carbon layer to efficiently inject electrons into pin diamond diode.

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