Diamond Schottky diodes for high power electronics

Diamond has a relatively wide bandgap but it can be made into a semiconductor, or even a metal, by doping it with impurity atoms. Semiconducting diamond layers, grown epitaxially on diamond substrates, have outstanding electrical and thermal properties in view of high power applications. Diamond high power devices are now being intensively investigated. In particular, Schottky diodes based on a metal/diamond junction appear very promising: high breakdown voltages up to 10 kV have been achieved, though unfortunately associated with a high forward resistance. In recent advances, we have made significant progress in minimizing the forward resistance and obtained unprecedented Figures of Merit for diamond Scottky junction devices.

Diodes for high power electronics are required to pass ever higher currents in the forward direction and to sustain ever higher voltages in the reverse direction. Such diodes will be used for example in high power switching in DC/DC convertors to supply electric motors. Driven by recent environmental protection requirements and cost reduction imperatives, new diodes are needed. They will have to sustain up to 3.3 kV reverse voltage while allowing 1 ampère forward current.

The Schottky potential barrier at a metal-semiconductor contact is ideal for fast switching, and for low voltage drop in the forward regime. To fabricate Schottky diodes from diamond, we deposit a metal electrode on an oxygen terminated, p-type (boron doped), semiconducting diamond epilayer. That layer was grown on top of a metallic (p^{++}) diamond epilayer which acts as the back contact. The pseudo-vertical structure realized is illustrated in Fig. 1.

To ensure good rectifying behavior, we have focused our work on various metal-diamond interfaces and have demonstrated that the readily oxidised metal zirconium (Zr) is an excellent candidate to make efficient Schottky barriers. Fig. 1 shows the current-voltage (I–V) characteristic at room temperature for one of our Zr/diamond Schottky diodes. Zirconium Schottky contacts exhibited an extremely good rectification behaviour characterized by a high current density of 10^3 A/cm^2 (at +6 V), and a reverse current density smaller than 10^{-8} A/cm^2 up to our maximum test voltage *Vmax* = -1000 V. Given the semiconductor layer thickness of 1.3 µm in our vertical structure, the reverse field reached was 7.7 MV/cm.

An important "Figure of Merit" used to evaluate high power Schottky diodes is the ratio $Vmax^2/(R_{on}S)$, where R_{on} is the specific forward resistance and S the diode surface. For room temperature Zr/p-diamond we have obtained an unprecedented value of 244 (in units of MW/cm^2). This value lies far above the limit for silicon (10 MW/cm^2). It is today the largest value reported for diamond Schottky diodes and may be compared to the theoretical value (1000 MW/cm^2).

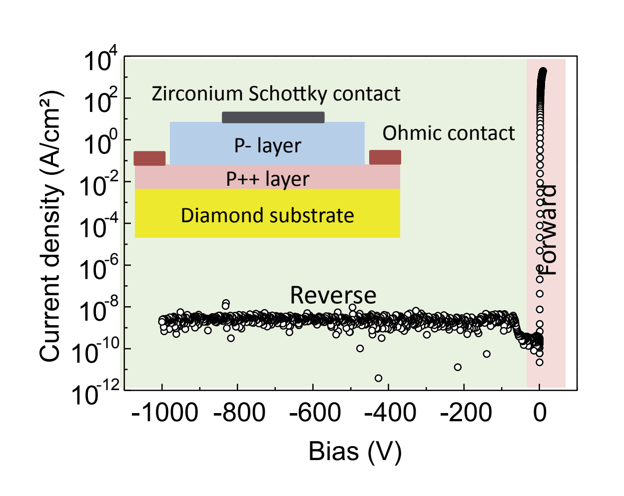

Fig. 1: Typical current-voltage characteristics at 300 K for one zirconium/p-type diamond Schottky diode deposited on a diamond substrate. The data show the high reverse voltage, and the high forward currents achieved.

A high resolution Transmission Electron Microscopy study undertaken by colleagues from the University of Cadiz (Spain) showed the presence of an oxide at the Zr/diamond interface (see Fig. 2). This oxide provides strong passivation of interface defects, which no doubt explains the excellent reproducibility of our I–V characteristics. For instance, 83 out of a total of 100 diodes characterized had reverse current below a threshold of 1.3×10^{-9} A/cm^2.

We have found that annealing our Zr/p-diamond Schottky diodes can reduce significantly the voltage threshold allowing high forward current. This is related to a reduction of the Schottky barrier height, e.g. from 1.88 eV for as-deposited diodes to 1.49 eV for diodes annealed at 350°C. Finally, we have measured a current of 1 A through a square (500x500 µm^2) diode. We should mention that several uncertainties affect the barrier height estimates, but Zr/p-diamond diodes annealed at temperatures as high as 450°C displayed a barrier height estimated at 1 eV, and the diode structure remained stable up to 500°C.

The performances reported here for Zr/p-diamond diodes confirm the potential of diamond for high power electronics applications. A French patent was filed in 2013 (ref. 13.53647 "Procédé de fabrication d'une diode Schottky sur un substrat en diamant").

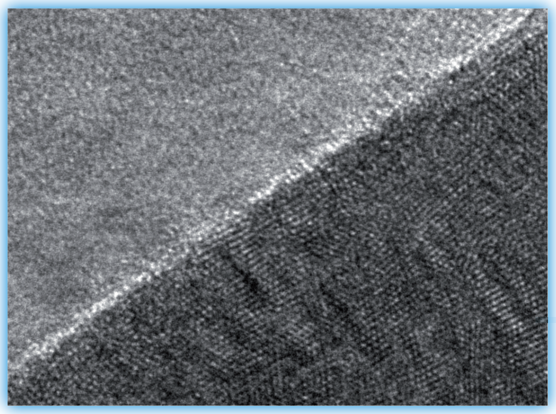

Fig. 2: High resolution Transmission Electron Microscope image of a Zirconium/Diamond interface lying in the [001] lattice plane. The bright atoms correspond to the oxide layer which passivates the interface. Courtesy of José Piñero (Cadiz University).

CONTACT

David EON
david.eon@neel.cnrs.fr

Ph.D student
Aboulaye TRAORE

FURTHER READING

Zr/oxidized diamond interface for high power Schottky diodes.
A. Traore, P. Muret, A. Fiori, D. Eon, E. Gheeraert and J. Pernot
Appl. Phys. Lett. 104, 052105 (2014)