Improved diamond devices with low active defect concentrations

Diamond is a "wide bandgap" semiconductor: E_G=5.4 eV, five times larger than that of silicon. It is considered as the ultimate material for fast, high voltage and high power electronics. Metal/diamond Schottky diodes and Metal/Insulator/Semiconductor (MOS) structures can now be fabricated in epitaxial diamond films grown on bulk diamond crystals. However, the device performance can be limited by defects or unwanted impurities located inside the diamond active layer. Using extremely sensitive electrical measurement techniques, we have now identified the principle defects restricting the flow of hole carriers in p-type diamond films, and we have investigated new growth techniques for eliminating them.

This work concerns the electrical properties of epitaxial diamond films grown at the Néel Institute on commercially available diamond substrates. The films are doped with the acceptor impurity boron to obtain p-type conductivity. Control of lattice defects and undesired impurities is essential, as these can trap carriers flowing in the valence or the conduction band. The defects are present in very low concentration, below the detection thresholds of most analysis and characterisation techniques. But they can be detected by their change in electronic charge or the transient current flowing in the bands when they release the trapped carriers (Deep Level Transient Spectroscopy measurements).

The measurement of the populations in the different charge states is done using a Schottky diode (Fig. 1). Through a voltage bias pulse applied to the Schottky electrode, the defects can be charged with holes to a non-equilibrium state. Capacitance transients or current transients are then measured when holes, initially trapped in a deep level pertaining to some defect, are emitted into the valence band. These transients are thermally activated because statistical thermodynamics apply in such a way that the emission rate increases with temperature.

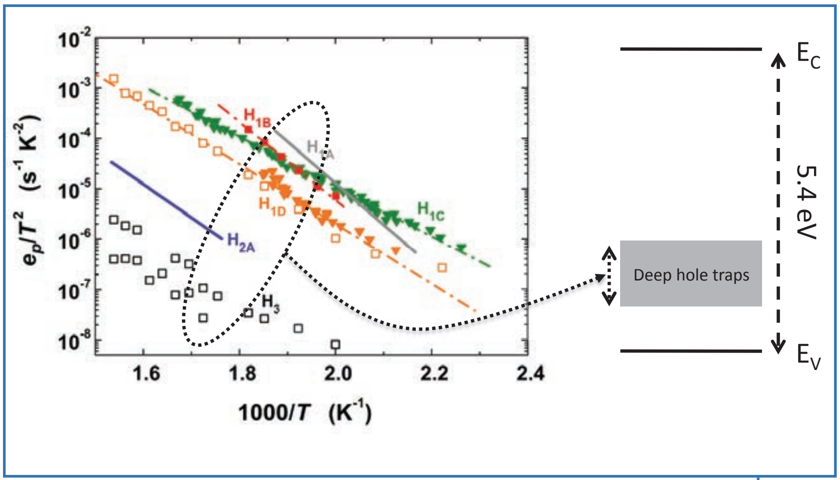
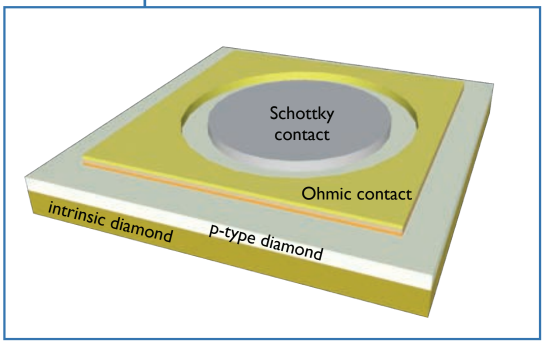


Figure 2: At left: Arrhenius diagram for deep hole traps in boron-doped diamond layers. The hole emission rate e_p divided by the square of the temperature is plotted against 1000/T. At right: energy range of the deep hole traps detected in the diamond band gap.

Figure 1: Schottky diode device fabricated on a diamond epilayer. These devices are used for determining the concentrations and ionisation energies of carrier-trapping defects



The emission rates are monitored as a function of temperature, via Fourier transforms of the transients (Fig. 2). This enables us to derive the ionization energy of the hole trapping defects, which is the main property for defect identification, as well as their concentration.

Many defects with hole ionization energies in the range 0.5-1.6 eV are detected (Fig.2). Theoretical calculations show that most of them can be attributed to complex centres comprising one or several atoms of boron and hydrogen, in some cases associated with a lattice vacancy (a missing carbon atom).

We have confirmed the role of hydrogen by preparing diamond layers with a small additional percentage of oxygen in the gas phase. This is known to dramatically decrease the H density on the surface and H incorporation in the bulk. These layers no longer show any hydrogen related deep levels. Consequently, this new recipe for diamond epilayer growth guarantees a defect-free material, at least for the deep levels due to hydrogen associated with boron atoms and/or a carbon vacancy.

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FURTHER READING

DEEP HOLE TRAPS IN BORON-DOPED DIAMOND
P. Muret, J. Pernot, A. Kumar, L. Magaud, C. Mer-Calfati and P. Bergonzo
Phys. Rev. B 81 (2010) 235205.

HOLE TRAPS PROFILE AND PHYSICAL PROPERTIES OF DEEP LEVELS IN VARIOUS HOMOEPITAXIAL DIAMOND FILMS
P. Muret, P.-N. Volpe, J. Pernot, F. Omnès
Diamond & Related Materials 20 (2011) 722.