POWER ELECTRONIC DEVICES BASED ON SINGLE-CRYSTALLINE DIAMOND

THE TASK

For the development of efficient power electronic devices, semiconductor materials with bandgaps larger than silicon are of particular importance. If diamond can be used instead of silicon, the electrical resistance and thereby the power loss of devices would be reduced by a factor of thousand and enable substantial energy savings in power electronics applications.

The next generation of power electronic devices following silicon, is based on silicon carbide (SiC) and gallium nitride (GaN). The intrinsic characteristics of diamond relevant for power electronic applications once again substantially exceed those of SiC and GaN (Fig. 1). If the isolation of 10 kV requires 1000 µm thick silicon devices and approximately 100 µm thick SiC or GaN devices, only 20 µm thick diamond devices are sufficient for the isolation of this voltage.

Currently, the expectations of diamond electronics are based on the comparison of intrinsic material characteristics and the possibilities derivable from them. The task therefore is to manufacture real power electronic devices from diamond and to practically demonstrate the theoretically expected advantages.

Selected properties of semiconductors with large bandgaps

	Si	6H-SiC	GaN	diamond
bandgap / eV	1.12	3.03	3.45	5.45
electric breakdown field strength / kV cm^{-1}	300	2500	2000	10000
thermal conductivity / W cm^{-1} K	1.5	4.9	1.3	22

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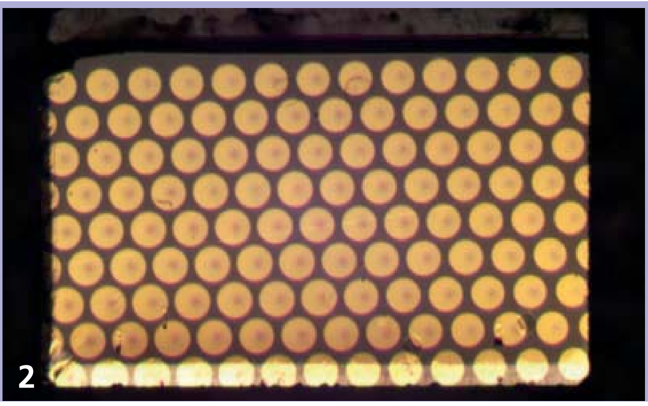
OUR SOLUTION

At the Fraunhofer Center for Coatings and Diamond Technologies CCD (see also p. 128), diamond diodes for power electronic applications are developed and fabricated in close collaboration with Michigan State University. The focus lies on vertical Schottky and Schottky pn junction diodes.

In the fabrication of diodes, the processes for the p- and n-doping of diamond are particularly challenging. At CCD the doping occurs during the plasma-based homoepitaxial growth of diamond crystals with boron as p-dopant and phosphorous as n-dopant. In a project financed by the U. S. Department of Energy (DE-AR0000455) the fabrication steps to produce diamond diodes are researched and optimized based on the achieved diode characteristics.

Three doping processes based on plasma-assisted CVD are currently the main focus. Two of the processes produce highly doped n- and p-type semiconducting regions. The third process produces lowly doped p-type regions. These doped regions were analyzed with diagnostic methods in order to determine their dopant concentration and electrical properties.

In a Hall effect measurement system, the electrical properties of the semiconductor are studied from room temperature up to 700 K. Measurements at these high temperatures are important, since special performances are expected of diamond devices in this range.



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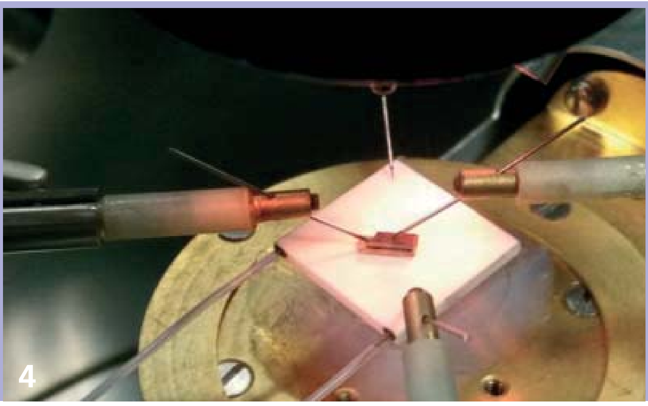

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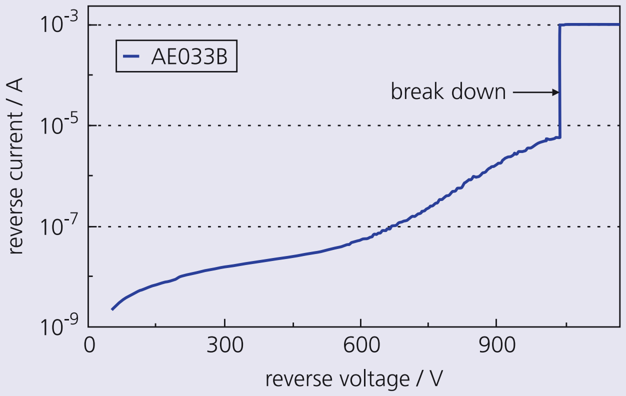
RESULTS

At 0.36 eV and 0.58 eV the activation energies of boron and phosphorous for the release of charge carriers are so high that at lower temperatures (e. g. room temperature), few charge carriers are available. Thus, the electrical resistance and the power loss in the forward direction of such doped regions are high.

Figure 2 shows a field of Schottky diodes produced at CCD, each with a diameter of 150 µm. The diamond region lightly doped with boron (dopant level = 1016 atoms cm^{-3}) is 10 µm thick. Many of these diodes achieved a breakdown voltage (voltage in reverse direction) of more than 1000 V in the test (see Fig. 3).

Current flow of a diamond Schottky diode biased in reverse direction; the breakdown occurs at 1040 V



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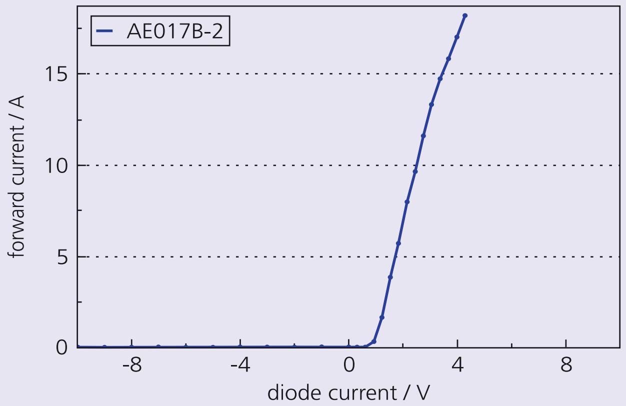
In highly doped diamonds, the activation energies are considerably lower. Furthermore, more charge carriers are released at higher operating temperatures (e. g. through heating). Simultaneously, diamond has a very large bandgap so that the material functions as a stable semiconductor at high temperatures. These considerations are taken into account in the design of electronic devices from diamond. Figure 4 shows another diamond Schottky diode with a contact surface of 1 mm x 2 mm. Figure 5 is the associated current – voltage graph. The diode has a lightly doped region of 10 µm thickness with a dopant level of 5 x 10^{17} atoms cm^{-3}. The forward current reaches up to 18 A.

Current-voltage graph of a diamond Schottky diode (1 mm x 2 mm) with a forward current of 18 A



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The results demonstrate the fabrication of diamond Schottky diodes as well as first promising voltage and current data. Present work focuses on building diodes that combine the properties of high forward currents with high breakdown voltages in one and the same device.

2 Diamond Schottky diodes with 150 µm diameter each

4 1 mm x 2 mm diamond Schottky diode being

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