

PRECISE BORON DOPING OF SINGLE-CRYSTALLINE DIAMONDS

THE TASK

Diamond is one of the most promising materials for applications in high-temperature, high-power and high-frequency electronics. The unique combination of extraordinary physical properties (Fig. 1) makes it possible to design electronic components that clearly exceed the performance of other semi-conductor elements (Si, SiC and GaN). A new generation of power electronic equipment that can be run with voltages of several 10 kV and a power from 100 kW to 5 MW is conceivable. Diamond-based power electronics are suitable for use at higher temperatures, without necessary external cooling and extensive protective circuits, saving both weight and costs.

To utilize the full potential of diamond electronics, the electrical properties of diamond, such as electrical breakdown field strength and charge carrier conductivity, have to be maximized, and precisely defined doping profiles have to be achieved for p- and n-doping. Fabrication of doping profiles with exact lateral and vertical sizes and defined acceptor and donor concentrations are the key to achieving semi-conductor transitions in diodes and transistors with controlled electrical fields and breakdown field strengths.

Physical properties of several semi-conductors

properties	Si	GaAs	6H-SiC	GaN	diamond
band gap, E_0 (eV)	1.12	1.43	3.03	3.45	5.45
breakdown field strength, E_c (kV cm ⁻¹)	300	400	2500	2000	10000
thermal conductivity, λ (W cm ⁻¹ K)	1.5	0.46	4.9	1.3	22

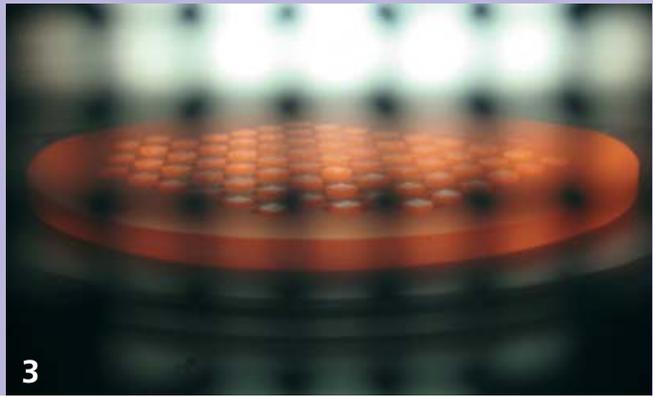
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OUR SOLUTION

Doping of diamond typically occurs with boron as the p-dopant and phosphorous as the n-dopant. Normally doping is performed in-situ during the homoepitaxial diamond synthesis by adding doping sources (for example in the form of a process gas) during the CVD process. However, direct doping during growth has a major disadvantage: it is impossible to vary the lateral doping profile. This is in stark contrast to other semi-conductor materials, in which doping is typically performed by ion implantation of the doping atoms and subsequent thermal curing.

For diamond, this method can only be implemented in a complicated manner, since diamond represents only a meta-stable carbon variant at atmospheric pressure. This mainly affects annealing, in which diamond may convert to graphite. Doping atoms do not diffuse well in diamond because the high atom density results in very low diffusion rates, unless the diamond is subjected to very high temperatures, at which, in turn, a conversion to graphite can occur.

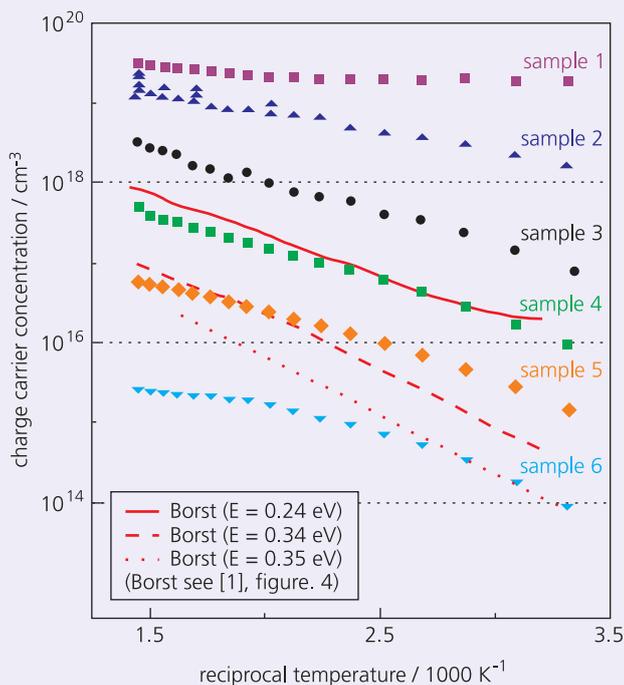
The Fraunhofer USA Center for Coatings and Diamond Technologies CCD, in conjunction with Michigan State University MSU, received a grant for a 4-year research project from the US National Science Foundation (NSF) to examine new doping methods for diamond to implement power electronics. The research focuses on further optimization of the doping process, even through alternative methods, such as diffusion of a solid doping source and ion implantation with doping atoms.



RESULTS

At Fraunhofer CCD, the synthesis of doped diamond is performed as in-situ doping in a standard process. During the CVD diamond synthesis (Fig. 3), the doping gases diborane (as n-dopant), and phosphine (as p-dopant) are added. Doping concentrations from 10^{15} cm^{-3} to 10^{20} cm^{-3} were achieved both with the p- and the n-dopant. Figure 2 depicts the defect concentration of Boron-doped diamond films at various doping concentrations, measured by the Hall effect. The study on in-situ doping is focused on the optimization of the growth process to reduce the defect density in the epitaxially grown layer. It is also important to vary the individual process parameters successively, so that defined doping concentrations can be deposited.

Charge carrier concentration in doped diamonds in a temperature range from 300 K (room temperature) to 700 K. The various samples were created with different doping gas concentrations.



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During diffusion, carbon films that include boron or phosphorous are deposited on the doping surface. Subsequently the compound is heated in a furnace in a nitrogen atmosphere at temperatures from 1000 °C to 1600 °C. The main goal of the study is to quantify the diffusion coefficients of boron and phosphorous in the diamonds as a function of temperature. The analysis is mainly based on SIMS and capacity-voltage (CV) measurements, and the determination of the material constants by using the Hall effect.

The process of ion implantation, hitherto only applied to separate diamond wafers without losses, is modified so that doping atoms are implanted near the surface. Heating to high temperatures leads to a homogeneous allocation of the doping atoms in the conductive layer. Doping of the conductive layer at very high doses (10^{19} cm^{-3}) and the integration of the foreign atoms in the diamond lattice are the greatest challenges in this study, since ion irradiation at too high doses disturbs the crystal lattice and converts these regions into graphite.

[1] Borst, T. H.; Weis, O.: Electrical characterization of homoepitaxial diamond films doped with B, P, Lo and Na during crystal growth, *Diamond and Related Materials* 4 (1995) 948-953

3 Homoepitaxial synthesis of 70 diamond crystals of $3.5 \times 3.5 \text{ mm}^2$ size

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