

Synthetic Diamond as an electronic material

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Research efforts are underway to develop advanced electronic devices based on synthetic diamond as the semiconductor material. What has made the potential exploitation of diamond as an electronic material possible is the breakthrough in diamond synthesis technology, specifically chemical vapour deposition (CVD) which allows single crystal CVD diamond to be manufactured to a high purity and consistency.

As an intrinsic electronic material, diamond has long been identified as having excellent properties particularly for high power and high frequency applications. These include: extremely high thermal conductivity, high hole and electron mobility, high dielectric strength and a wide band gap (see Fig.1). When compared to other materials for use in electronics, including silicon and gallium arsenide, the intrinsic properties of single crystal CVD diamond are clearly superior for applications where there are extreme demands (Fig.2).

As silicon is such a low cost and well established electronic material, the opportunity for synthetic, CVD diamond comes in those applications where silicon and other more conventional electronic materials cannot provide a solution today such as in the extremes of high power, high frequency applications. Traditionally, these applications have used Travelling Wave Tubes (TWTs); devices based on vacuum technologies rather than the solid-state.

Diamond is one of nature's best electrical insulators so the question is, can diamond be doped so that it can be used as an active switching device? Researchers have found that boron is a suitable p-type dopant. While a number of n-type dopants are being investigated such as phosphorus and sulphur, and primitive p-n junctions formed, the right electrical properties that could form the heart of a commercial switching device have thus far remained illusive.

In diamond, the boron dopant atoms form an acceptor band located at 0.37eV above the valence band edge. At room temperature, electrons from the valence band are thermally promoted to the boron acceptors leaving holes in the valence band to support the flow of current.

This means that most of the efforts are focused on developments based upon synthetic, single crystal CVD diamond doped with boron to form p-type, unipolar devices. A number of different types of electronic devices incorporating diamond have been proposed efforts are moving towards the development of commercial devices. These include diodes and various types of field effect transistors.

Devices in diamond

One of the first electronic devices to be developed at E6 was a diamond Schottky barrier diode. This diode was the result of a collaboration with researchers at Cambridge University's Engineering department and the power electronics company, Dynex Semiconductors. This device could challenge SiC and GaN in wide bandgap applications such as traction motor control and power distribution. In theory, the operating voltage could extend up to 10 kV for diamond-based Schottky diodes, while the attributes of diamond would allow operation at higher temperatures

than other wide-bandgap semiconductors.

The ability to create transistor-type switches in diamond would open up niche, but still large markets in high frequency and high power applications. Eventually, this new solid-state technology could challenge travelling wave tubes that are currently at the heart of the amplifiers used for satellite communications and used widely in radar, particularly in airborne fire-control radar systems, and in electronic warfare and counter-measures.

Researchers in search of a high power, high frequency switching device based upon a MESFET (Metal Semiconductor Field Effect Transistor) structure, have been experimenting with the use of "delta doping". Here, thin layers of highly boron-doped diamond buried within the intrinsic diamond material donate carriers (holes) creating a conducting channel between metal source and drain contacts. The current is modulated via a Schottky gate. (Note: MESFETs are high frequency devices used to make RF power amplifiers and are usually constructed in GaAs, InP, or SiC).

Other examples of a field effect transistor (FET), including a diamond thin-film, include (1) devices based upon the surface conduction induced in the diamond near surface by a thin layer of hydrogen and (2) other work also announced in Japan has described a FET having a structure in which a high-resistance diamond layer is placed between an insulating single crystal diamond substrate and a semiconducting diamond layer, the structure is referred to as a pip structure.

Out of the Lab

Over the next few years, companies are aiming to move this research work out of the laboratory and into real products. Element Six is investing in a new venture called Diamond Microwave Devices (DMD). Its remit is to develop novel synthetic diamond semiconductor materials and processing technology that will help create the next generation of high power, high frequency electronic devices for use in electronic warfare and wireless communications systems. If the company can demonstrate a practical semiconductor device based upon CVD diamond, it would have potential to provide superior microwave performance over many existing solid-state devices and other emerging technologies such as GaN and has the potential of revolutionising microwave power electronics.

	Si	SiC-4H	GaN	Diamond
Band gap (eV)	1.1	3.2	3.44	5.5
Breakdown field (MV/cm)	0.3	3	5	20
Electron mobility (cm ² /Vs)	1450	900	440	4500
Hole mobility (cm ² /Vs)	480	120	200	3800
Thermal conductivity (W/cm.K)	1.5	5	1.5-3	24
Johnson's Figure of Merit	1	410	280	8200
Keyes' Figure of Merit	1	5.1	1.8	32
Baligas Figure of Merit	1	290	910	17200

Figure 1: Material properties and figures of merit (normalized to Si) at room temperature. The numbers under diamond are those recently reported by E6 for electronic grade CVD diamond.

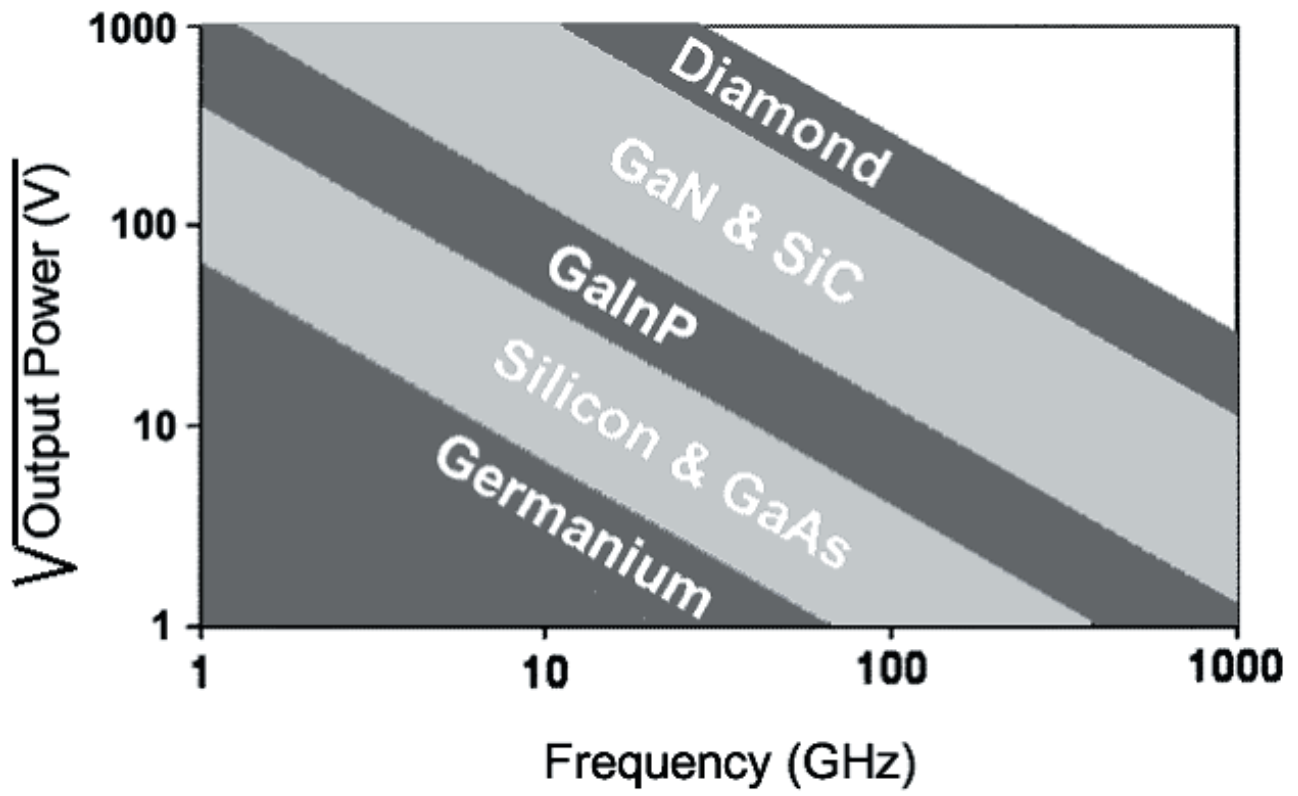


Figure 2: Output power achievable as a function of frequency of different material semiconductors for 1 Ohm output impedance.