Unlocking diamond’s potential as an electronic material

BY R. S. BALMER 1, I. FRIEL 1, S. M. WOOLLARD 1, C. J. H. WORT 1, G. A. SCARSBROOK 1, S. E. COE 1,*, H. EL-HAJJ 2, A. KAISER 2, A. DENISENKO 2, E. KOHN 2 AND J. ISBERG 3

1Element Six Ltd, King’s Ride Park, Ascot, Berkshire SL5 8BP, UK
2Department of Electron Devices and Circuits, University of Ulm, Ulm 89069, Germany
3Department of Engineering Sciences, Ångström laboratoriet, University of Uppsala, PO Box 256, Uppsala 571 05, Sweden

In this paper, we review the suitability of diamond as a semiconductor material for high-performance electronic applications. The current status of the manufacture of synthetic diamond is reviewed and assessed. In particular, we consider the quality of intrinsic material now available and the challenges in making doped structures suitable for practical devices. Two practical applications are considered in detail. First, the development of high-voltage switches capable of switching voltages in excess of 10 kV. Second, the development of diamond MESFETs for high-frequency and high-power applications. Here device data are reported showing a current density of more than 30 mA mm\(^{-1}\) along with small-signal RF measurements demonstrating gigahertz operation. We conclude by considering the remaining challenges which will need to be overcome if commercially attractive diamond electronic devices are to be manufactured.

Keywords: diamond; electronics; CVD; transistor

1. Introduction

It has long been recognized that diamond’s extreme properties make it a very attractive material for electronic applications. In particular, its wide bandgap, high carrier mobility and excellent thermal conductivity mean that it could excel in semiconductor applications requiring high frequency and power. Recent advances in synthesis technology (Sussmann 1993) mean that it is now possible to manufacture diamond of sufficiently high quality so that its use in electronic applications can at last be seriously considered. Nevertheless, there remain huge challenges to move from the raw diamond material available today to practical, high-performance semiconductor devices in the future.

In §1a, we consider the quality of synthetic diamond, which can now be manufactured, and assess its suitability for electronic applications. The practical challenges in making doped devices are considered in §1b. We review practical

* Author for correspondence (steve.coe@e6.com).

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progress on making actual devices for both high-voltage and high-frequency applications in §§2 and 3, respectively. Section 4 considers the remaining challenges that will need to be overcome to make practical devices.

(a) Chemical vapour deposition diamond and its application as an electronic material

The technology to manufacture polycrystalline synthetic diamond by chemical vapour deposition (CVD) is now well established (Sussmann 1993; Sussmann et al. 1998; Coe & Sussmann 2000). This allows the production of diamond in sizes and with specific material characteristics not readily found in nature or achieved by other more conventional synthesis technologies such as high-pressure high-temperature manufacture. As a result, CVD diamond products have been successfully developed for a range of market applications, including heat spreaders, infrared windows, detectors, cutting tools and acoustic products (www.e6.com). More recently, the capability to produce single-crystal CVD diamond has been developed to the point where it is starting to be introduced as a commercial product for several applications (figure 1).

If we now consider diamond as an electronic material, it can be seen in table 1 that it has a range of properties that offer the potential of extreme device performance.

Even in the group of wide bandgap materials, which includes silicon carbide (SiC) and gallium nitride (GaN), diamond can be considered extreme in its intrinsic electronic properties as shown in figure 2. It is the unmatched

Table 1. Electronic properties of diamond.

<table>
<thead>
<tr>
<th>property</th>
<th>value</th>
<th>potential device application benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td>wide bandgap</td>
<td>5.5 eV</td>
<td>high temperature</td>
</tr>
<tr>
<td>high thermal conductivity</td>
<td>24 W cm(^{-1}) K(^{-1})</td>
<td>high power</td>
</tr>
<tr>
<td>high electric breakdown field</td>
<td>10 MV cm(^{-1}) (predicted)</td>
<td>high voltage</td>
</tr>
<tr>
<td>high carrier mobility</td>
<td>(\mu_0 \sim 3800) cm(^2) Vs(^{-1})</td>
<td>high frequency</td>
</tr>
<tr>
<td>high bond strength</td>
<td>(V_{\text{sat}} \sim 0.8 \times 10^7) cm s(^{-1})</td>
<td>radiation hard</td>
</tr>
<tr>
<td></td>
<td>(5.8 \times 10^{-19}) J per bond</td>
<td></td>
</tr>
</tbody>
</table>

Figure 1. Single-crystal diamond plates manufactured by CVD and suitable for use in mechanical and optical applications.
combination of highest bulk thermal conductivity, high carrier mobility and high breakdown voltage that makes diamond a truly multifunctional material and will allow applications in environments simply too demanding for other materials and devices. As a result, diamond electronic devices, such as power diodes and high-frequency field-effect transistors (FETs), can be expected to deliver outstanding performance.

To develop diamond as an electronic material, it requires the ready availability of an intrinsic material with the properties described above. Recent advances in CVD diamond synthesis technology have meant that it is now possible to produce single-crystal diamond with properties consistent with electronic applications (Isberg et al. 2002). While the size of individual samples remains modest (5–10 mm), they are still sufficient to form a test bed for the fabrication of practical prototype devices.

(b) Doping of CVD diamond

Dopants in wide bandgap semiconductors tend to have higher ionization energies than those in narrow bandgap semiconductors, resulting in low activation at room temperature. For example, 4H–SiC has shallow donors (n-dopant), but lacks a shallow acceptor (p-dopant), the shallowest being aluminium with an ionization energy of 0.19 eV (Ikeda et al. 1980). In the case of diamond, known dopants have even higher ionization energies. The most common dopants used in diamond are listed in table 2 with their associated ionization energy.

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Reports claiming that sulphur (S) or oxygen (O) constitute comparatively shallow donors remain to be substantiated at the time of writing. A boron–hydrogen complex has also recently been reported to constitute a shallow n-type dopant (Chevallier et al. 2002), but the long-term stability of this complex is uncertain. As boron is readily incorporated into CVD diamond as a dopant impurity, there has been much activity focused on unipolar devices using boron. However, boron acceptors are only weakly activated at room temperature due to the ionization energy of 0.37 eV. To mitigate this, the boron solid concentration must be increased to very high levels where the conduction mechanism changes first from band-type conduction to hopping, and then eventually to metallic-like as the acceptor bands begin to overlap the valence-band maximum and the activation energy approaches zero (Nebel & Stutzmann 2001). At the same time, the presence of compensating donors (shallow or deep) must be minimized. This metallic-like conduction results in a much lower bulk resistivity.

It can be concluded that, while intrinsic diamond with properties suitable for electronic applications is now available, significant challenges remain in terms of successfully doping the material. As a result, the high activation energies of currently available dopants in diamond have encouraged researchers to explore less conventional device designs. Two such approaches are considered in the rest of this paper.

2. High-voltage applications

The unique properties of CVD diamond, particularly its large bandgap, high dielectric strength and high thermal conductivity, suggest that the material should be an ideal semi-conducting medium for high-voltage and high-power switching applications. To avoid the limitations of available dopants, we have considered the use of an external source of either UV photons or electrons to generate charge carriers in the diamond and trigger conduction. The exceptional electronic properties of synthetic single-crystal CVD diamond would appear ideally suited to such an approach, provided that (i) a suitable trigger source can be identified which meets both the switching speed and the on-state conductivity requirements and (ii) a practical diamond-based device configuration can be realized.

(a) Simulation of a possible device concept

The total free charge required to trigger the onset of the breakdown varies with the applied field. For a given charge, we need to know the onset voltage and, conversely, for a given voltage, we need to know the minimum charge. Dynamic
(i.e. time-dependent) simulations using drift–diffusion and Poisson equation of the avalanche onset have been performed for the simple device as shown in figure 3. The key focus of the investigation was whether the transit of charge (electrons or holes) through the device can alter the electric field within the device sufficiently to modify the avalanche behaviour.

The modelled device consists of intrinsic diamond with ideally blocking front and back contacts as shown in figure 3. The front contact consists of concentric rings to allow for the light or e-beam to enter the diamond. UV photons with less than 225 nm wavelength have energy larger than the bandgap of diamond (5.5 eV). Indirect (photon-assisted) electron–hole pair generation across the bandgap will occur upon illumination by light with these wavelengths. The absorption of photons in this process is very strong, so carriers are generated only in a few micrometres closest to the illuminated surface of the sample.

A low-energy electron beam will also be strongly absorbed resulting in carrier generation occurring again only within a few micrometres of the surface. The concentric rings were chosen so as to get an axisymmetric device amenable to two-dimensional simulations, as full three-dimensional simulations are not feasible (or necessary). One-dimensional simulations, where both contacts are assumed massive and of infinite extent, can also be run. The one-dimensional simulations require much less computation time, so it is possible to carry out parameter studies. The disagreement between the one- and two-dimensional simulations turns out to be rather small. The main difference between the two is that the current differs by a constant factor.

The tool used for the simulations is based on a commercial finite-element modelling software, COMSOL Multiphysics (www.comsol.com). This software was chosen as it is more versatile than dedicated device simulators. It is our experience that, with these latter packages, convergence can be difficult to achieve in wide bandgap materials like diamond. The device modelling tool now includes, in addition to the impact ionization model, Shockley–Read–Hall recombination and a velocity saturation model. The device is assumed to be illuminated by a short pulse of either above bandgap light (shorter wavelength

![Figure 3. Schematic of an externally pumped high-voltage switch.](http://rsta.royalsocietypublishing.org/Downloaded from)
than 225 nm) or by a strongly absorbed e-beam. In both cases, owing to the low penetration depth, a space-charge region near the front contact will be created.

When charge carriers are injected (using photon or e-beam excitation) into an intrinsic semiconductor, or alternatively into the depletion region of a reverse-biased diode, a high enough electric field can accelerate the charges to velocities where the impact ionization becomes important. This can lead to avalanche ionization in the semiconductor as shown in figure 4. An avalanche could be used to extend a current pulse over time, even if the trigger pulse that generates the initial charge carriers is short. Thereby the necessary power in the trigger pulse can be reduced and a shorter trigger pulse is needed.

It should be noted that a number of the material parameters for diamond have significant uncertainty at the present time. The largest uncertainty is in the values of the impact ionization coefficients. Therefore, there are also large uncertainties in predicted values such as the breakdown voltage. The saturation velocity (of holes or electrons) has a rather strong influence and is also not well known. However, the uncertainty due to this is smaller than the uncertainty due to the impact ionization coefficients. The mobility (of hole or electrons) has little influence on the results as electric fields are high and rapidly saturate in velocity. However, it should be stressed that the qualitative conclusions from the simulations still hold within a wide range of the coefficients.

(b) Results from simulations

Dynamic avalanche simulations clearly show that the space charge of the carriers can affect the electric field sufficiently to initiate avalanche breakdown in the device. Parameter studies of the device represented in figure 3 have been performed for the conditions summarized in table 3.
Two cases of the injection profile were considered: one with somewhat deeper penetration with an exponential profile decaying by $1/e$ per every 3 $\mu$m, to emulate 213 nm optical irradiation, and another with shallower penetration to emulate irradiation by a low-energy e-beam. The illumination pulse is assumed instantaneous, or at least much shorter than the onset of the avalanche.

Figure 5 shows an example of how the onset of the breakdown is strongly dependent on the injected charge, with a fixed bias over the device (in this case, 20 kV). Below a certain threshold, the avalanche dies out rapidly (nanoseconds). Above the threshold (approx. 70 nC), the avalanche develops fully. Of course, this threshold effect is a very desirable or even necessary property since it means that spurious events with low energy (such as random thermal fluctuations, shot noise, background radiation, etc.) will not be able to trigger the device.

These dynamic avalanche simulations clearly show that impact ionization can generate avalanche breakdown provided sufficient initial charge is present. However, for a real switch delivering power into a load, the voltage across the switch drops as the current increases, and it may no longer be possible to sustain the generation of new carriers. To test this, the finite-element model of the switch was incorporated into a circuit simulator. Simulations of the switch with just a resistive 50 $\Omega$ load in series all show that the avalanche never really develops and very little gain is observed.

To remedy this problem, a capacitor was added in parallel with the switch (figure 6) to uphold the voltage over the switch during the first few crucial nanoseconds so that enough carriers (electron–hole plasma) are created during the initial avalanche process. With a suitably chosen capacitor, this turns out to work very well.

Figure 5. Four transient simulations showing current through a device for four different injection levels. The bias is 20 kV. Clearly, there is a threshold injection level (in this case, between 55 and 70 nC) that must be exceeded in order to achieve a breakdown.

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For a 20 kV, 400 A switch, circuit simulations were performed with the device data chosen as in Table 4. The simulations were made for a range of different bias voltages and amounts of injected charge by the trigger.

The simulations show that it is possible to achieve pulses of approximately one hundred nanoseconds in duration in this way. Figure 7 shows the current pulse through the load for a bias of 20 kV and an injected charge by the trigger of $Q_{\text{inj}}=3\times10^{-7}$ C (sufficiently high to ensure avalanche breakdown). Figure 8 shows in more detail the rising flank of the current with a short rise time, approximately 1 ns. The data are summarized in Table 5.

### Table 4. Data for a 20 kV switch in example below.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>thickness</td>
<td>150 μm</td>
</tr>
<tr>
<td>dopant concentration</td>
<td>0</td>
</tr>
<tr>
<td>active area</td>
<td>1 cm²</td>
</tr>
<tr>
<td>$R_{\text{load}}$</td>
<td>50 Ω</td>
</tr>
<tr>
<td>$L_{\text{stray}}$</td>
<td>10 nH</td>
</tr>
<tr>
<td>$C_s$</td>
<td>1 and 10 nF</td>
</tr>
<tr>
<td>injection profile</td>
<td>optical 213 nm</td>
</tr>
<tr>
<td></td>
<td>3 μm (exponential profile)</td>
</tr>
</tbody>
</table>

(c) 20 kV switch

For a 20 kV, 400 A switch, circuit simulations were performed with the device data chosen as in Table 4. The simulations were made for a range of different bias voltages and amounts of injected charge by the trigger.

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(d) Conclusions from numerical simulations

Device simulations clearly show that it is possible to initiate a dynamic avalanche in bulk diamond and deliver power into a 50 Ω load. The avalanche effect results in a gain of approximately 100–1000, making it possible to use a much smaller and cheaper trigger source than for a purely photoconductive switch (without gain).

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Possible trigger sources

The avalanche switch concepts modelled in §2a rely on the near instantaneous creation of at least 70 nC of charge within the diamond near the surface. Two types of radiation are practical triggers for diamond-based, monoblock switches, namely: (i) electromagnetic radiation (UV and X-rays) with appropriate intensity and wavelength and (ii) electron beams. In both cases, the carriers are generated within the diamond material. The key to achieving a fast, high-power switch is being able to rapidly generate enough sufficiently mobile carriers. Carrier lifetime is only an issue if it is short compared with the required on-time of the switch.

Figure 7. Current through a 50 Ω load for two values of the capacitor $C_s$. The bias voltage $V_A = 20$ kV; the injected charge by the trigger pulse $Q_{inj} = 3 \times 10^{-7}$ C.

Figure 8. Detail of the rising flank in figure 7 showing an approximately 1 ns rise time assuming an infinitely short trigger pulse at time zero. For a realistic trigger pulse of (say) 1 ns duration, the rise time will increase correspondingly.

(e) Possible trigger sources

The avalanche switch concepts modelled in §2a rely on the near instantaneous creation of at least 70 nC of charge within the diamond near the surface. Two types of radiation are practical triggers for diamond-based, monoblock switches, namely: (i) electromagnetic radiation (UV and X-rays) with appropriate intensity and wavelength and (ii) electron beams. In both cases, the carriers are generated within the diamond material. The key to achieving a fast, high-power switch is being able to rapidly generate enough sufficiently mobile carriers. Carrier lifetime is only an issue if it is short compared with the required on-time of the switch.

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To achieve the avalanche, our simulations suggest that a charge in excess of approximately 70 nC is required, regardless of how the charge is generated. However, sources of deep UV photons with sufficient output intensity and fast enough turn-on times are not currently commercially available (other than excimer lasers that are prohibitively expensive), so the only practical trigger source mechanism would be irradiation with electrons. Suitable grid-switched electron guns are commercially available.

3. High-frequency applications

Owing to physical limitations, silicon and gallium arsenide devices are unlikely to achieve power levels higher than a few hundreds of watts depending on the frequency to be amplified. Wide bandgap materials, in principle, allow for higher power output per unit gate length at microwave frequencies. This is because a larger bias voltage, and hence the voltage amplitude on the microwave signal, can be supported across the transistor channel region over which the current is modulated. This is made possible by the high breakdown electric fields of wide bandgap semiconductors. In microwave power transistors, the ability to support high voltage is particularly desirable, since power is typically transferred to a relatively high impedance (e.g. 50 Ω) load. Diamond, with its extreme physical properties, could potentially replace high-power vacuum tube devices by solid-state components in certain niche applications. If the intrinsic properties of diamond can be fully exploited through a novel device design and fabrication, diamond devices could be applicable to the entire RF generation market up to 100 GHz.

(a) Diamond MESFET for high-power, high-frequency applications

A conventional MESFET device design is shown diagrammatically in figure 9. Ohmic current transport takes place between the source and drain contacts until the saturation velocity, \( v_{sat} \), is reached. The maximum channel current \( J \) is proportional to \( qN_A t v_{sat} \), where \( t \) is the channel thickness and \( N_A \) is the acceptor concentration. But to be in the metallic conduction regime requires that \( N_A > 10^{20} \text{ cm}^{-3} \), which would mean that the mobility of holes in the channel is significantly degraded due to ionized impurity scattering.

Thus, owing to the high ionization energy of boron-doped diamond, conventional device designs cannot be expected to yield high-performance RF devices. Instead, a more creative approach to a device design is required in order

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Table 5. Summary of data for the 150 μm, 20 kV switch with two different values of \( C_s \).

<table>
<thead>
<tr>
<th></th>
<th>( C_s = 1 \text{ nF} )</th>
<th>( C_s = 10 \text{ nF} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>bias, ( V_a )</td>
<td>20 kV</td>
<td>20 kV</td>
</tr>
<tr>
<td>injected charge, ( Q_{inj} )</td>
<td>( 3 \times 10^{-7} \text{ C} )</td>
<td>( 3 \times 10^{-7} \text{ C} )</td>
</tr>
<tr>
<td>maximum current, ( J_{max} )</td>
<td>400 A</td>
<td>400 A</td>
</tr>
<tr>
<td>pulse duration, ( t_{90} ) (90% of the maximum current)</td>
<td>52 ns</td>
<td>112 ns</td>
</tr>
<tr>
<td>charge through load, ( Q_{load} )</td>
<td>( 3.6 \times 10^{-4} \text{ C} )</td>
<td>( 2.0 \times 10^{-4} \text{ C} )</td>
</tr>
<tr>
<td>avalanche gain, ( Q_{load}/Q_{inj} )</td>
<td>122</td>
<td>660</td>
</tr>
</tbody>
</table>
to use the superior properties of intrinsic diamond. In particular, it would be highly desirable to achieve some degree of spatial separation between ionized acceptors and holes. Several workers have made use of the unique ability in diamond to create a conductive (p-type) layer on the H-terminated surface (so-called ‘surface transfer doping’). We will not discuss surface devices in this paper, but impressive progress has been made by several groups with headline figures, which include an output power density of $2.1 \text{ W mm}^{-1} \text{ cw}$ at 1 GHz ($V_{DS} = -16 \text{ V}$, $L_g = 0.3 \mu\text{m}$, $W_g = 2 \times 50 \mu\text{m}$; Hirama et al. 2006) and $f_T = 45 \text{ GHz}$ and $f_{\text{max}} = 120 \text{ GHz}$ ($V_{DS} = -18 \text{ V}$, $L_g = 0.1 \mu\text{m}$, $W_g = 50 \mu\text{m}$; Ueda et al. 2006). Although these results are promising, the long-term stability of these surface FETs remains an issue, particularly at elevated temperatures and in harsh environments.

(b) P-i-P FET

Alternative design concepts that have been investigated and which aim to use charge transport in intrinsic CVD diamond are shown diagrammatically in figure 10. The P-i-P MISFET design is similar to the basic design shown in figure 9, except that a trench is etched through the doped conducting channel. Gate dielectric and metal are deposited into the trench as shown in figure 10a. This design was pioneered by Kobe Steel (Kawakami et al. 2005) based on space-charge ideas discussed in Isberg et al. (2002). The current that flows around the gate is space-charge limited, which is not ideal for a high-power transistor. Furthermore, successful operation requires very precise etching of the gate trench with nanometre control, as the source–drain current is highly sensitive to the effective gate length ($L_{\text{eff}}$).

(c) Delta FET

A more attractive design is shown in figure 10b, which incorporates a degree of separation between the holes and ionized acceptors by the introduction of a ‘delta’ doping layer, a technique pioneered in silicon devices and commonly used in III–V devices. The delta layer is a very thin (a few monolayers ideally), highly boron-doped region sandwiched between ‘undoped’ intrinsic diamond. Most of the conduction occurs in the intrinsic layers due to diffusion of holes from the narrow delta-doped layer. The mobility in the delta layer with a doping concentration of approximately $10^{20} \text{ cm}^{-3}$ would be in the region of $1–10 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$, whereas it may be as high as $3800 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ in the intrinsic regions. Numerical simulation predicts that, for a delta-layer thickness of approximately 2 nm, up to 95% of the hole transport will take place outside the delta layer in the intrinsic channel (A. Denisenko 2006, private communication). An enhanced variant of the single-delta MESFET is the
double-delta MESFET as shown in figure 10c. Here an additional boron-doped layer is deposited on top of the structure, which is used to make contact to the delta layer and thus improve the source and drain ohmic contact properties.

While offering performance advantages, the delta-layer design presents formidable synthesis challenges. Principal among these are the requirements to prepare atomically smooth, defect-free diamond surfaces, and the growth of nanometre-thin layers with atomically abrupt interfaces. This is challenging in any material, but, for diamond grown by microwave CVD, it is particularly complicated owing to the presence of the plasma and the difficulty of preparing a flat and smooth substrate surface.

(d) Boron delta-layer growth

Secondary ion mass spectrometry (SIMS) is commonly used to assess the boron concentration in doped diamond layers. Figure 11 shows boron profiles from the SIMS analysis of two delta-layer structures grown by microwave CVD.

Figure 11a,b is a single-delta and a double-delta structure, respectively. By careful tuning and optimization of the growth conditions, a very abrupt rising edge (nearest to the surface) of the doping peak is observed in both cases, with a gradient of 1 nm per decade of boron concentration. The asymmetry observed may be an artefact of the SIMS measurement. There are three important points to note with these profiles: first, the peak boron concentration is approximately $10^{20}$ atm cm$^{-3}$, which is crucial for carrier activation at room temperature; second, the interfaces
are very abrupt and the peaks are narrow; and third, the boron concentration in the material at either side of the doping spike is low (close to the SIMS background).

\[(e)\] Device fabrication and testing

Devices have been fabricated on single-delta structures using aluminium as the gate metal and precise etching of the top intrinsic diamond cap layer was employed to create ohmic contacts to the delta layer using a tungsten silicide metallization scheme.

Figure 12 shows a room temperature DC output characteristic for a single-delta device demonstrating a peak output current density of more than 30 mA mm⁻¹. The channel is fully pinched off at lower source–drain voltages, but at a higher bias the observed leakage current indicates that carrier conduction may be occurring through the substrate.

Small-signal RF measurements have been performed on single-delta devices. Figure 13 shows data extracted from $S$-parameters for one such device, which demonstrates very promising results for the cut-off frequency, $f_T > 1$ GHz, and the maximum frequency of operation, $f_{\text{max}} \sim 4$ GHz.

In summary, it can be seen that the first ‘proof of concept’ diamond MESFET structure has been successfully fabricated. At this stage, it appears feasible that further improvements in the delta-layer manufacture and device fabrication should yield substantial improvements in device performance consistent with achieving commercially attractive devices.

4. Future developments and conclusions

It has been demonstrated that it is now possible to manufacture single-crystal diamond demonstrating sufficiently attractive electronic properties to form a starting point to fabricate practical devices. Nevertheless, there remain huge
challenges to overcome in establishing practical methods of generating sufficient charge carriers in diamond to facilitate practical devices. Currently, available dopants are too deep to allow the fabrication of more conventional device designs. As a consequence, effort has been devoted to more novel designs which circumnavigate some of these difficulties. Initial results presented here show that these approaches have sufficient promise that these concepts are worthy of further investigation and may yet unlock diamond’s potential as an electronic material.

Figure 12. DC output characteristic for a single delta device with $L_G=0.7 \mu m$ and $W_G=30 \mu m$ measured at room temperature.

Figure 13. Small-signal RF performance extracted from $S$-parameters for a single-delta structure showing a cut-off frequency $f_T > 1$ GHz and the maximum frequency of operation $f_{\text{max}} \sim 4$ GHz.
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References


Discussion

AUDIENCE MEMBER. What gate isolation material do you use which has a higher breakdown field strength than diamond?

R. S. BALMER. Under operating conditions, the peak electric field occurs at the gate edge. Some designs have incorporated alumina (deposited by ALD) as the gate dielectric with a measured $E_{\text{BD}}$ of 7 MV cm$^{-1}$. Alternatively, high-quality intrinsic O-terminated diamond is the material between gate metal and channel.

If the peak field remains an issue, then field control strategies such as field-plate technology can be employed at the expense of parasitic capacitance, and hence maximum operating frequency. In short, this is a very topical question!