Diamond-MESFETs – Synthesis and Integration

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Abstract

We report the utilization of synthetic diamond grown by chemical-vapour-deposition (CVD) for use as metal-semiconductor field-effect-transistors (MESFETs). The lack of a shallow n-type donor means that diamond-based electronic devices are unipolar (p-type). The devices presented in this paper are based on delta-doping. Delta-doping stands for the use of very thin (<5 nm) highly doped ($N_A > 10^{20}$ cm^{-3}) buried layers. This approach poses a huge challenge in terms of synthesis as well as processing. First successful attempts of fully integrating working delta-doped diamond MESFETs are presented.

Keywords: Diamond MESFET, delta-doping

Introduction

Current semiconducting materials do not offer high power RF (>8 GHz) devices in simple solid-state device configurations which will be required for compact, phased array radar applications. Wide-band gap materials such as GaN, SiC and Diamond all offer the potential for such RF devices and of these materials diamond has by far the best material characteristics [1].

The generation of HF and microwave signals is now mostly based on silicon and gallium arsenide devices. Due to physical limitations, these devices cannot achieve power levels higher than a few hundred watts (depending on the frequency to be amplified) in simple solid-state device configurations which will be required for future compact, phased array radar applications. Wide band-gap materials (diamond, SiC, GaN etc), in principle, allow for higher power amplification 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. In effect, the higher breakdown electric field of a wide band-gap semiconductor is exploited. In microwave power transistors, the ability to support high voltage is particularly desirable, since, generally, power has to be transferred to a relatively high impedance (50 Ω) load.

Diamond, with its extreme physical properties, will allow a real breakthrough by allowing the replacement of high power vacuum tube devices by solid-state components. Theoretically, the intrinsic performance of diamond suggests that diamond devices could take the entire RF generation market up to 100 GHz (producing 100s Watts at X-band frequencies). Preliminary microwave devices based on diamond have been demonstrated by two teams [2,3], with a current gain cut-off frequency, f_t, above 11 GHz showing that diamond is now entering the world of HF electronics.

Recent advances in the use of chemical vapour deposition (CVD) to grow free standing single crystal intrinsic and boron doped diamond means that we may finally be at the dawn of the diamond electronics era [1,4].

Doping of Diamond

Diamond compared with other semiconductors is rather difficult to dope, this is largely due to its bonding and its small lattice parameter. These characteristics make it hard to incorporate extrinsic impurities into the diamond lattice.

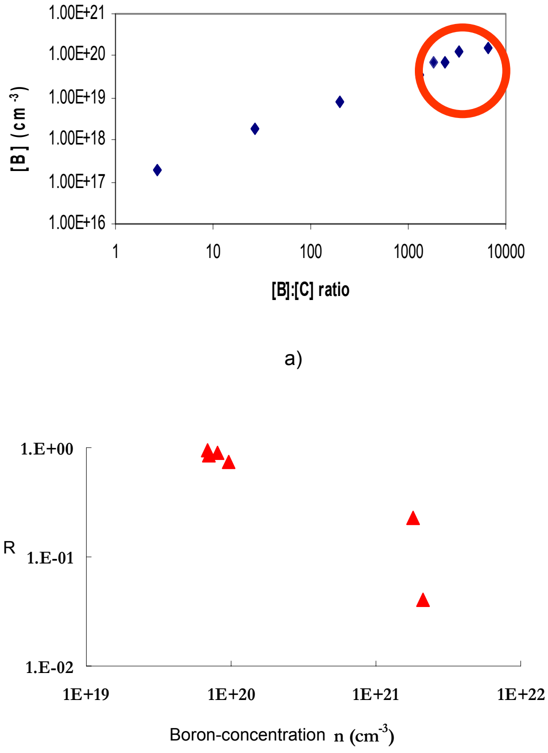
Therefore the possible candidates for diamond doping are limited. Boron is used for p-type doping, while Nitrogen and Phosphorous are the best candidates for n-type doping. All of these dopands are deep. The boron-acceptor has got an activation energy of E_A=0.37 eV. N and P donors exhibit even higher activation energies of 1.7 eV and 0.62 eV respectively [5].

The donors are therefore not activated at room-temperature at all, while B as an acceptor is at least partially activated at room-temperature. However, full acceptor activation at room-temperature can be achieved for B-doping levels higher than 10^{19}cm^{-3} where hopping dominates the carrier transport. For B-doping levels higher than 3x10^{20}cm^{-3} a metal-insulator-transition takes place [6].

Since it is extremely challenging to achieve these high acceptor concentrations in CVD-diamond it has until recently not been possible to demonstrate the above mentioned changes in acceptor activation-energy in single-crystal CVD-diamond.

Figure 1a shows that boron-incorporations as high as 2x10^{20} cm^{-3} in free-standing single-crystal CVD-diamond films have been demonstrated for the first time. In figure 1b it is shown how these high boron-concentrations lead to the predicted rapid drop in resistivity

In addition hydrogen-terminated diamond-surfaces display p-type conductivity in a near-surface conductive channel with a sheet-charge of approximately 10^{13} cm^{-2}[7]. However, the origins of this effect remain unclear. A detailed review dealing with these instability issues can be found in [8].



a)

b)

Figure 1: Very high [B]-concentrations in single-crystal diamond measured by SIMS; B:C is the gas-phase ratio (a) and drop in resistivity R (b).

Thus, diamond devices are restricted to p-type unipolar devices and cannot easily be designed with fully activated doping. Principally one is left with two choices to realize RF-power-electronics: using very high B-concentrations for reduced acceptor activation energy, or hydrogen-induced surface channels, generated without external doping. In this study the possibility of reduced carrier-activation-energy by achieving very high doping concentrations is being explored.

Delta-Doping

As discussed above for devices such as FETs, which require high current-densities at room-temperature, the doping-concentration of the conducting channel needs to exceed 10^{19} cm^{-3}. On the other hand, the channel sheet charge, which can be fully modulated by the Gate, is limited by the breakdown-field in the Gate-diode structure. With a breakdown-field of intrinsic diamond of 10 MVcm^{-1} this sheet charge density needs to be between 10^{13} cm^{-2} and 10^{14} cm^{-2} to enable full channel pinch-off by the Gate.

The doping profile needs therefore to be extremely narrow (so-called ‘delta-doping’) with a thickness smaller than 5 nm. Delta-doping has in the past successfully been applied within III-V compound systems [9].

The reproducible growth of highly boron-doped diamond-layers with thickness within the nm-range poses a huge technological challenge, although first successful attempts have been reported [10].

These challenges lie within the controlled, reproducible CVD-growth of these layers itself – nanometer-precision of growth/etch of the delta-layers as well as uniformity of the delta-layers in terms of composition and thickness over the device dimensions (> 10 µm). In addition to that it is also necessary to use atomically-smooth growth substrates (diamond) – something that in itself can be seen as rather challenging for a material as difficult to process as diamond.

To be able to assess the quality of the delta-layers the chosen characterisation-technique is secondary-ion-mass-spectroscopy (SIMS) – giving an insight in both the layer-thickness as well as the boron-concentration.

However, an additional advantage of the delta-layers is the fact that, if overgrown by an intrinsic diamond layer, most of the hole transport will occur outside the delta-layer in the intrinsic layer.

Whereas the mobility at a doping concentration of 10^{20} cm^{-3} would be in the region of 10 cm^{2}V^{-1}s^{-1}[6], it may be as high as 3800 cm^{2}V^{-1}s^{-1} in the intrinsic part[1]. Quantum-mechanical calculations as presented in [9] predict that for a delta-layer-thickness of 2 nm 95% of the hole transport will take place above the delta-layer in the intrinsic channel.

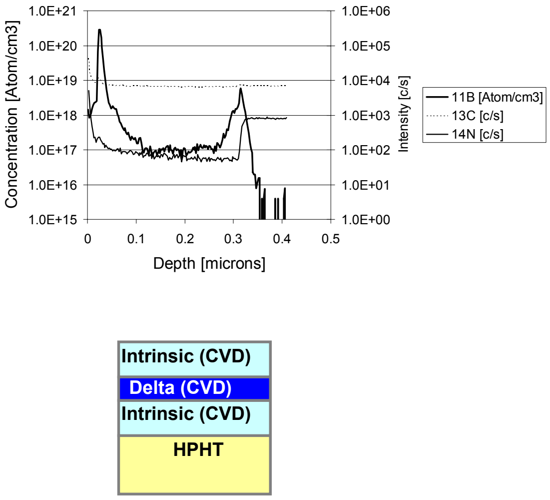


Figure 2: SIMS-profile of diamond delta-layer covered by thin intrinsic layer.

First successful attempts to grow delta-layers within this project are shown in figure 2. It shows the SIMS-spectrum of a substrate similar to the one shown in the figure.

A high-pressure / high-temperature (HPHT)-grown diamond (100)-substrate was first overgrown by a 250 nm thick intrinsic CVD-diamond buffer-layer. A boron-doped delta-layer with a FWHM-thickness of 10 nm was deposited on top of the buffer- layer. As shown in figure 2 the boron-concentration within the delta-layer is as high as 5x10^{20} cm^{-3}. Finally an intrinsic diamond layer with a thickness <

20 nm was deposited on top of the delta-layer.

Besides having been able to grow a thin, highly boron-doped delta-layer, it is worth mentioning that the interface between the delta-layer and the intrinsic top-layer is very sharp – the boron-concentration drops rapidly from 5×10^{20} cm^{-3} down to 4×10^{18} cm^{-3}. Although the boron-concentration of the intrinsic channel should ideally be as low as 10^{15} cm^{-3} to ensure as little as possible Coulomb-scattering with ionised impurities of the holes in the intrinsic channel, this observation can be seen a proof that the chosen approach in terms of deposition-technology is leading into the right direction.

Device Design and Fabrication

Due to substrate processing requirements, and to avoid the already mentioned surface conductivity of H-terminated diamond surfaces, the substrate surfaces are oxygen terminated. Since oxygen-terminated surfaces have a pinned surface potential at 1.7eV above the valence band [11] the Ohmic contacts need to be tunnelling contacts. This can be realized by using heavily doped diamond contact areas. Therefore the Ohmic contacts are deposited directly onto the delta-layer.

The chosen Ohmic-contact metallization for Source- and Drain-contacts consists of a 20 nm thin amorphous tungsten-silicide-layer covered by a gold capping-layer. The WSi alloy consists of 33% Si in W and is deposited by e-beam-evaporation of a WSi-target.

As already mentioned, in our current device design (figure 3) the Ohmic contacts are deposited directly on top of the boron-delta-layer. This approach offers the additional benefit of the region of high carrier density (the interface between the delta-layer and the intrinsic channel) being accessible by the Source- and Drain-contacts.

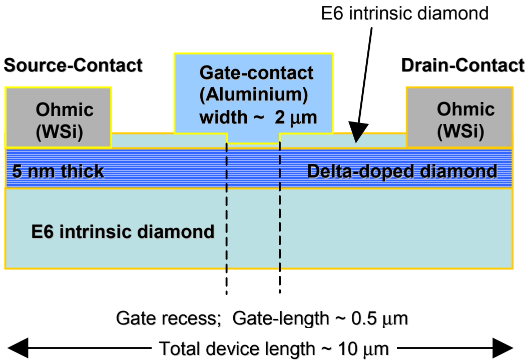


Figure 3: E6-diamond MESFET device structure.

WSi offers the advantages of high temperature-stability and selective-area epitaxy, since because of the comparatively high Si-content diamond does not nucleate on WSi[11]. These are very desirable characteristics of the chosen contact scheme since the the intrinsic channel layer is deposited on top of the delta layer after the Ohmic contact metallization step – thus reducing the number of processing steps.

In addition to the above mentioned advantages the WSi-metalization scheme is also compatible with standard optical lithography techniques.

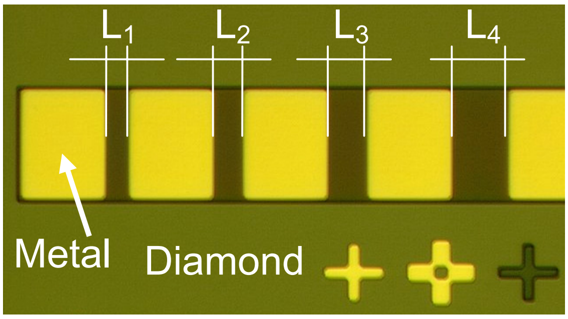


Figure 4: TLM test-structure to evaluate Ohmic Source and Drain-contacts.

Transmission-Line-Measurements (TLM) [12] were performed in order to assess the specific contact resistance ρ_C of the WSi-contacts (figure 4). The specific contact resistance is independent of the contact-geometry and gives a direct measure of the resistance of the WSi/delta-layer-interface.

TLM is a technique that allows to deduce ρ_C by eliminating the bulk-contribution to the total resistance R_C between two Ohmic contacts. This is achieved by measuring R_C between various pairs of identical Ohmic contacts with different spacings d between each other and then by plotting R_C over d. A detailed describtion of this method can be found in [12]. The specific contact-resistance ρ_C that was deduced from the measured total resistance R_C of the WSi-contacts was as low as $1x10^{-4}\Omega\mu^2$.

Any non-carbide-forming metal will form a Schottky contact on an oxidised diamond surface [11]. In our design we are using an aluminium Schottky-contact which is deposited directly onto the intrinsic channel using e-beam evaporation. A Schottky barrier-height of 1.3 eV has been measured for this Gate-configuration (figure 5). Detailed results regarding the research into diamond-based Schottky diodes at Element Six Ltd. have been reported in [13].

The fact that the intrinsic channel forms part of the Schottky Gate-diode means that an extremely low contamination with boron is required to ensure a low-leakage Schottky Gate-contact.

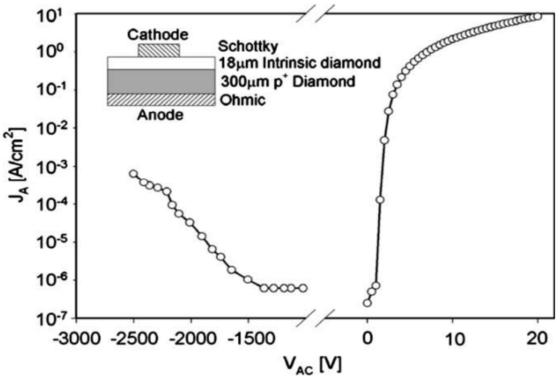


Figure 5: Diamond Schottky-diode Gate-metal test-structure.

Since the surface is effectively shielded by the oxygen-termination the Gate needs to be recessed to obtain enhancement of the Gate-performance and to avoid parasitic resistances (figure 4). While the overlying Al-contact pad has a width of 2 µm the actual Gate-length of the recessed Gate is only 0.5 µm with a Gate-width of 100 µm.

Since this Gate-recess is etched into the nm-thin intrinsic channel and care has to be taken to avoid the recess trench contacting the delta-layer, nm-precise etching has to be applied. This is done by using Reactive Ion Etching (RIE) in an Ar/O2 plasma where etch rates down to as little as 1.5 nm min^{-1} have been obtained.

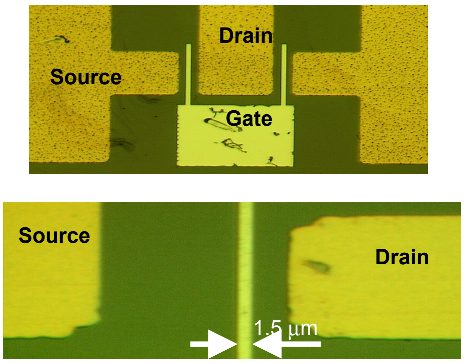


Figure 6: Top-view of MESFET structure.

Figure 6 shows an image of the actual diamond MESFET structure being integrated on a single-crystal CVD-diamond substrate. In figure 7 transistor-like I-V-curves are shown. This data was obtained measuring the electrical performance of the first set of diamond MESFETs produced during the first year of this project. Although the Source-Drain-current I_{SD} is still below 1µA these results can be seen a successful proof of principle, especially if one considers all of the above mentioned challenges.

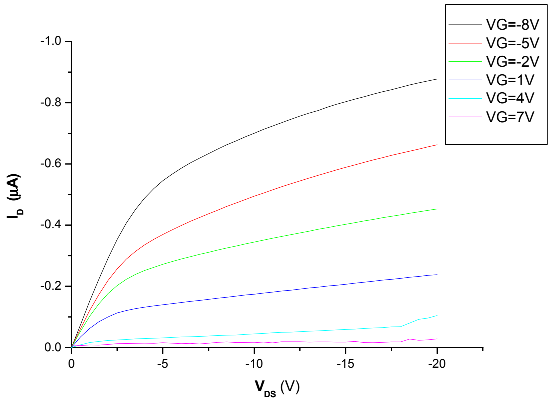


Figure 7: Transistor-like I-V-curve of a diamond MESFET.

As can be seen form figure 7 I_{SD} can be fully pinched-off by the Gate. The reason for the device not reaching complete saturation is the fact that we are still only at the beginning in terms of nm-precise-deposition of the delta-layer and the intrinsic-layer. Further, the growth-substrate preparation (atomically flat surfaces) is still a challenge in addition to the very complex processing technology necessary for diamond MESFETs.

Summary

This paper describes the preliminary work leading to CVD-diamond-based high-power / high-frequency MESFETs conducted at Element Six Ltd in collaboration with Ulm University, Germany, during the first year of this EMRS DTC sponsored project.

During this period first demonstrator-devices exhibiting transistor-like current-voltage characteristics have successfully been integrated. In order to get this far various initial challenges in terms of material synthesis, device design and processing have been overcome. First delta-doped layers have been deposited and have successfully been overgrown with equally thin intrinsic diamond channels. An Ohmic contact scheme has been developed that besides showing a very low specific contact resistance also is compatible with standard processing requirements. Al-Schottky-diodes as Gate-contacts have shown to be able to deliver full channel pinch-off.

References

1 J.Isberg et al., Science, 297 (2002), 1670
2 H. Umezawa et al, IEEE Electron Device Letters, 23 (2002) p121
3 A. Aleksov et al, IEEE - EDL, 23(8), (2002) p488
4 G. Amaratunga, Science, 297 (2002) p1657
5 A. Collins, Semicond. Sci. Technol., 4 (1989), p605
6 C. Nebel EMIS 26 p40
7 H. Kawarada, Surf. Sci. Repts., 26 (1996) p205
8 M. Riedel et al., Phys. Rev. B, 69 (2004) p125338
9 T. Kobayashi et al., J. Appl. Phys., 76 (1994) p1977
10 M. Kunze et al., Carbon 37 (1999) p787
11 A. Aleksov et al., Semicond. Sci. Technol., 18 (2003) pS59
12 M. Schwitters, Diploma Thesis, Oldenburg (Germany)1999
13 D.J. Twitchen et al., IEEE Trans. El. Dev., 51 5 (2004) p826

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