Practicalities of Using Diamond as an Active Electronic Device Material

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Abstract

This paper considers in detail the limitations of diamond as an electronic device material and then goes on to discuss how these apparently considerable barriers to device realisation may be mitigated. Mitigation is possible through novel device design and by playing to the considerable strengths of CVD diamond as both a material and a technology. By way of an example, the realisation of a high frequency, diamond-based MESFET device is described.

Keywords: Diamond, CVD, doping, MESFET

Diamond Electronics

It has long been recognised that the mono-elemental, covalently bonded cubic structure of diamond not only leads to the extreme properties, but also suggests diamond may be a potentially excellent electronic material. The advent of diamond synthesis by Chemical Vapour Deposition (CVD) during the mid. 1980s sparked considerable interest in the possibility of realising diamond-based electronics. However, the interest waned after ten years due to the inability to produce suitable intrinsic and doped diamond electronic materials at that time.

More recently, "electronic quality" intrinsic and doped diamond single crystal materials have been reported [1,2,3] renewing interest in CVD diamond electronics. One of the most impressive and useful characteristics is the fact that intrinsic CVD-diamond displays a hole-mobility of 3800 $cm^2V^{-1}s^{-1}$. Although intrinsic diamond has exceptional electronic properties [1], and has a range of uses as a detector, the vast majority of "active devices" will also require at least one doped diamond material. Both p-type [2] and n-type [3] single crystal diamond materials have been reported, but the dopants are very deep (0.37eV and 0.6eV for boron and phosphorous, respectively) and thus the energies required to get sufficient carrier activation may prevent the realisation of "traditional" electronic devices at normal temperatures. The lack of a native oxide and the chemical inertness of diamond combined with the small size of wafers currently available seem to suggest that traditional device fabrication techniques may not be applicable to diamond.

High-frequency signals such as microwaves are generated with devices mostly based on silicon and gallium arsenide. These devices, due to the limitations of the semiconducting materials, 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. A route towards device that deliver higher output powers at higher frequencies (like X-band) is the utilization of wide band-gap materials such as diamond, SiC, or GaN. Devices based on these materials would in principle allow for

higher power amplification per unit gate length at microwave frequencies.

Particularly in diamond with its high predicted breakdown-voltage of 10 MV/cm [1] it is expected that larger bias voltages (enabling a higher 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.

Doping of CVD-Diamond

In order to be able to use a nominally insulating material such as diamond as a semiconductor the electrical properties of the material need to be altered by doping. Strong bonding and a small lattice parameter limit the number of possible candidates for diamond doping. 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 [4]. Because the n-type donors are too deep this work focuses on unipolar p-type devices only. This choice limits the possible device designs.

However, even B as an acceptor is not activated at room-temperature. For full acceptor activation at room-temperature B-doping levels higher than 10^{19}cm^{-3} where hopping dominates the carrier transport. Boron-concentration levels higher than $3x10^{20}$cm^{-3} lead a metal-insulator-transition as described in [5]. Over the last two years Element Six has managed to overcome these challenges [6].

Delta-Doping of CVD-Diamond

The downside of bulk boron-concentrations in the region of $1x10^{20}$cm^{-3} is the drop in hole-mobility that occurs proportional to the increase in the amount of dopant being present in the bulk [6]. The key advantage of diamond – high carrier mobility – is lost in these regions and it is therefore necessary to separate the carriers from the regions of high doping concentrations. In addition, 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^{12} cm^{-2} and 10^{13} cm^{-2} to enable full channel pinch-off by the gate.

As a consequence of the above mentioned constraints extremely narrow doping-regions with a thickness smaller than 5 nm are required. This so-called 'delta-doping' has in the past successfully been applied within III-V compound systems [7].

A key objective of this work is precise delta-doping using CVD techniques. Many challenges lie in the controlled, reproducible CVD growth of these layers – nanometer precision as well as uniformity in terms of composition and thickness over the anticipated device dimensions (> 10 μm). For the growth of these layers it is necessary to use substrates with surfaces which are smooth on the atomic scale, and generate sharp interfaces between doped and undoped layers. To assess the quality of the delta-layers the chosen characterisation technique is secondary-ion-mass-spectroscopy (SIMS) which helps to get an insight in both the layer thickness as well as the boron concentration.

Theoretical work predicts that for delta-layers overgrown by an intrinsic diamond layer with a sharply defined interface, most of the hole transport will occur outside the

delta-layer in the intrinsic layer [7]. 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}[5], 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.

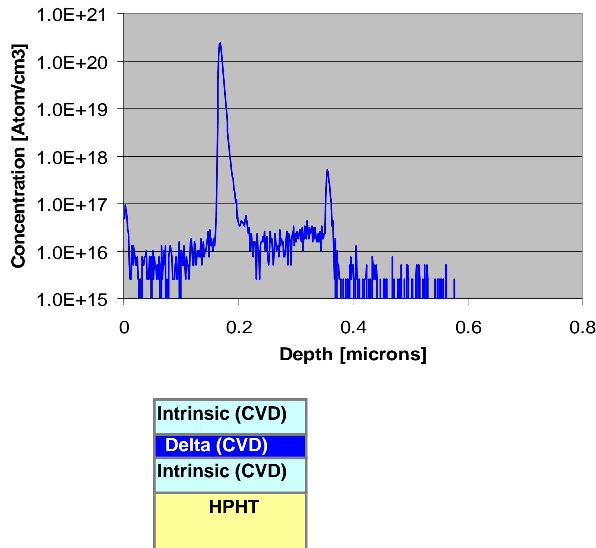

Figure 1: SIMS-profile of diamond delta-layer covered by thin intrinsic layer.

First successful attempts to grow delta-layers within this project have been reported [6]. Figure 1 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 100 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 5×10^{20} cm^{-3}. Finally an intrinsic diamond layer with a thickness 100 nm was deposited on top of the delta-layer to simulate a real device and also to have the delta-intrinsic interface positioned well away from the top surface of the sample, since it is known that surface contamination can influence the SIMS signal near the surface area.

One of the key achievements in this work is growing these thin, highly boron doped delta-layers with a very sharp intrinsic top-layer – the boron-concentration drops rapidly from 5×10^{20} cm^{-3} down to $< 4 \times 10^{16}$ cm^{-3}, which is the detection-limit of the SIMS-equipment used. This appears to validate the synthesis methods used.

Device Design and Fabrication

One potential unipolar device design based on the use of delta-layers is described below. This design is preliminary and it is anticipated that for devices in terms of high-frequency and power more sophisticated designs will need to be implemented. Other designs are currently under investigation.

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. 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[8]. Furthermore WSi-metalization is also compatible with standard optical lithography techniques These are very desirable characteristics of the chosen contact scheme since 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. As already mentioned, in our current device design (Figure 2) the ohmic contacts are deposited directly on top of the top boron-delta-layer. This approach offers the additional benefit of a region of high carrier density forming in the intrinsic channel

underneath the ohmic contact between the top and bottom delta-layers. It is expected that this approach leads to an improved ohmic contact scheme.

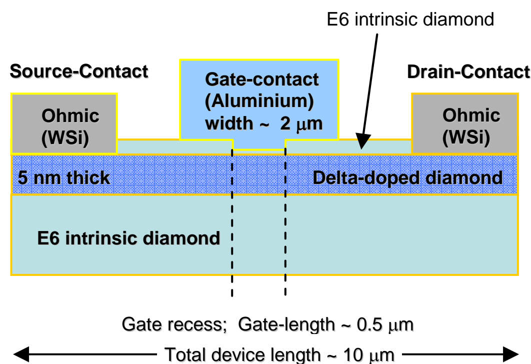

Figure 2: E6-diamond MESFET device structure.

Transmission-Line-Measurements (TLM) [9] were performed in order to assess the specific contact resistance ρ_C of the WSi-contacts. The specific contact-resistance ρ_C that was deduced from the measured total resistance R_C of the WSi-contacts was as low as $1x10^{-4}\Omega cm^2$.

For the gate a Schottky-contact is required. Any non-carbide-forming metal will form a Schottky contact on an oxidised diamond surface [11]. As reported previously aluminium Schottky-contact for the gate. A Schottky barrier-height of 1.3 eV has been measured for aluminium Schottky contacts on boron-doped diamond [10].

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.

The gate-recess is etched into the nm-thin intrinsic channel. Therefore care has to be taken to avoid the recess trench contacting the bottom delta-layer. As a consequence nm-precise etching has to be applied. This is done by using Reactive Ion Etching (RIE) in an Ar/O2 plasma with etch rates down to as little as 1.5 nm min^{-1}.

Conclusions

We present the status of this EMRS-supported work at the end of project-year 2. It has been possible to improve the CVD-only delta-doping significantly. In addition it has been possible to demonstrate a very sharp interface between the boron-doped layers and the intrinsic CVD-diamond layers. This is an important step towards realizing diamond-based high-power high-frequency transistors.

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