Alternative High Power RF FETs Based Upon CVD Diamond

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Abstract

With its many extreme properties, single crystal CVD diamond is an attractive material for high power and high frequency electronic device applications. DMD is developing novel, diamond-based material systems, structures and device fabrication processes in order to achieve a high performance diamond microwave transistor. In this paper we review the progress made on evaluating two alternative RF device designs, with the objective of comparing their relative performance and merits against DMD's emerging delta-doped devices.

Introduction

In high power, high frequency pulsed applications where physical size and weight are a premium, wide bandgap (WBG) materials like GaN and diamond have the potential to replace travelling wave tube (TWT) technology. If the intrinsic properties of diamond (as summarised in Table 1) can be fully exploited, diamond devices could have a significant impact on the RF generation market up to 100 GHz. However, the high activation energies of dopants in diamond makes it necessary to explore less conventional device designs, such as delta-doped FETs with very highly doped layer in the active region of the device.

Table 1. *Important material properties of single crystal CVD diamond which make it an ideal candidate for high power, high frequency electronic devices.*

Diamond property	Applicability to device operation
Wide Bandgap	High temperature
High thermal conductivity	High power
High breakdown field	High voltage
High carrier mobility and saturation velocity	High frequency
High bond strength	Radiation hard

Delta- FET

Currently under development at DMD is the delta-FET design which incorporates an ultra-thin highly boron 'delta' doped layer, sandwiched between 'undoped' intrinsic diamond. For a doping concentration of $>10^{20}$ cm^{-3}, the activation energy of the boron acceptor tends to zero. The design relies on diffusion of holes from the narrow delta-doped layer into the high mobility intrinsic layers.

Whilst overcoming the limitations of doping diamond, the delta-layer design presents formidable synthesis challenges. Principal amongst these are the requirements to prepare atomically smooth diamond surfaces free of damage, and the growth of nm-thin layers with atomically abrupt interfaces. This is challenging in any material, but for diamond grown by microwave CVD, it is particularly complicated due to the presence of the plasma and the difficulty of preparing a flat and smooth substrate surface.

Alternative device designs that can take full advantage of the exceptional intrinsic properties of diamond are obviously attractive and this report describes the progress towards the development of two such concepts: the surface conduction FET (SURFET) and the polarisation-enhanced FET (PEFET).

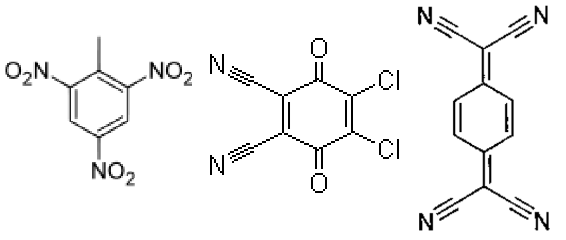
Surface conduction FET (SURFET)

Hydrogenated diamond surfaces allow the transfer of electrons from the diamond into a surface acceptor (usually water vapour from the atmosphere) resulting in a hole accumulation layer within the diamond near surface region. In prior art, FETs have been fabricated using this structure and have demonstrated good transistor characteristics and RF performance [1, 2]. However, these devices are not environmentally stable and degrade rapidly under operation. The solution, and the novelty of this work is to replace the atmospheric water with an environmentally stable electron acceptor and thus retain the RF performance over time and operation.

DMD and Element Six are working with partners to identify alternative surface moieties based on conjugated aromatic polymers that not only induce surface conduction (which occurs provided the Fermi level in diamond is similar in energy to the lowest unoccupied molecular orbital or LUMO of the overlayer) but also provide environmental stability. It is hoped that through engineering of the diamond, efficient transfer doping is achieved and the resulting FETs produced are environmentally stable. DMD and partners are exploring novel compounds for coating diamond that provide stable transfer doping and the development of novel routes for the deposition of monolayer films of these compounds to the diamond. INEX are developing contact technology and the fabrication of test structures.

Electron Accepting Compounds

Several compounds have been identified which are conjugated (resulting in a general delocalization of the electrons across all of the adjacent parallel aligned π-orbitals of the atoms) and with a sufficiently low LUMO making them suitable as electron acceptors on hydrogen terminated diamond. They include 2,4,6-trinitrotoluene (TNT), 2,3-Dichloro-5,6-dicyano-1,4-benzoquinone (DDQ) and 7,7,8,8–tetracyanoquinodimethane (TCNQ), see Fig. 1.



TNT DDQ TCNQ

Fig. 1: *Conjugated compounds identified as suitable electron acceptors.*

Investigation of TCNQ coating by deposition

In this work, we have focused on the TCNQ family of compounds and investigated a range of deposition techniques onto H-terminated diamond surfaces as a proof of principle of charge transfer. To ensure good conductivity across the sample, the TCNQ layer has to form an extended network across the surface, maintaining good contact with the surface throughout. TCNQ is a highly crystalline compound; the degree of completeness of the deposited layer will depend upon the ability of the method of deposition to allow the TCNQ crystals to grow on the surface. In all of the deposition methods attempted, TCNQ was mixed with acetonitrile and dissolved using an ultrasonic bath for 5 min to furnish a 5% w/v mixture.

Experiments have shown that spraying, dipping and spin coating are not viable techniques for depositing TCNQ films. However, successful deposition of continuous TCNQ films consisting of an extended network of TCNQ crystallites on H-terminated diamond has been achieved using evaporation. The diamond substrate was heated to 85-90°C on a hot plate, and 0.05ml of the TCNQ formulation was added to the surface. The solvent was immediately evaporated and the substrate was allowed to cool to room temperature. An extensive investigation of the deposition conditions (focusing on the effect of concentration, solvent and temperature of evaporation) looking at TCNQ thickness uniformity and topography was undertaken. Samples were examined optically and using profilometry.

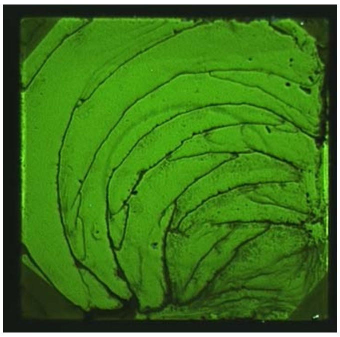


Fig. 2: *Optical image of TCNQ coated diamond sample using the evaporation method.*

Optical microscopy showed that continuous films of TCNQ were successfully deposited (Fig. 2), but for all conditions investigated, the films were characterised by a highly textured 'mountain-range' topography with a peak to valley up to 1 – 10 μm due to the non-uniform crystal growth of the TCNQ film. The films were assessed using SEM and FTIR, but the thickness of the films prevented detection of electron transfer at the TCNQ/diamond interface.

Electrical assessment of TCNQ coated samples was made using photolithographic techniques to define metal contacts. However, the thickness and topography of coated samples is not compatible with standard lithography, therefore hydrogen-terminated intrinsic diamond samples were first patterned with a series of standard circular TLM structures using TiPtAu contacts, then coated with TCNQ using the evaporation method. The coating appeared to be continuous across the sample, over metal and exposed diamond. However, when electrical probes were placed on the contacts, the TCNQ film had a strong tendency to flake off resulting in poor cross-sample consistency of I-V data. Nevertheless, several contacts exhibited much higher current after coating as shown in the I-V plots in Fig. 3, which strongly indicates that the H-termination was maintained and charge transfer occurred resulting in conductive samples. Analysis gave a sheet resistance of 30 kΩ/sq. This result is higher than the expected 10 kΩ/sq but may be due to the thickness and poor morphology of the TCNQ film.

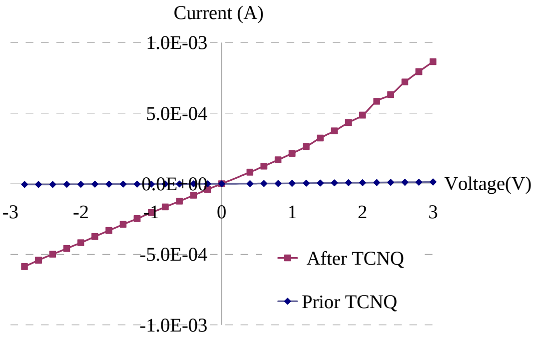


Fig. 3: *I-V characterisation of contacts on H-terminated diamond with and without TCNQ coating.*

Polarisation enhanced FET (PEFET)

The polarisation-enhanced field effect transistor (PEFET) concept is based on the use of a thin polar layer attached to the surface of an intrinsic single crystal diamond layer. The difference in polarisation between these two layers (diamond is non-polar) gives rise to an electric field which can be used to attract charge carriers to the interface between the two materials, thus forming a two dimensional gas [3, 4]. This 2D gas of carriers forms the channel of the PEFET device. This is a significant advantage of the PEFET over the delta-FET design, as ionised impurity scattering is effectively eliminated resulting in much higher mobilities.

To successfully realise a diamond PEFET with a high mobility channel, it is important that the polar layer does not contain domains of mixed polarity, but should be a single polarity layer. In addition to this, the band discontinuities between the two materials should be such that either electrons or holes (or both) are confined to the high quality, high mobility diamond layer. In this work, AlN has been investigated as the polar layer. AlN films were deposited on type Ib single crystal diamond substrates by plasma-assisted molecular beam epitaxy. Film microstructure was characterised by transmission electron microscopy (TEM) and convergent beam electron diffraction (CBED), while the band offsets between the diamond and AlN layers were characterised by x-ray photoelectron spectroscopy (XPS).

TEM characterisation of AlN / diamond microstructure

As reported previously [3, 5], AlN layers grown on {100} diamond exhibit a mosaic microstructure characterised by two families of domains misorientated with respect to each other by a 30° rotation about the polar c-axis. However, this does not preclude realisation of a PEFET as long as neighbouring domains are of the same polarity. Fig. 4 shows a cross sectional TEM image of an AlN film grown on {100} diamond with diffraction vector g = (0002).

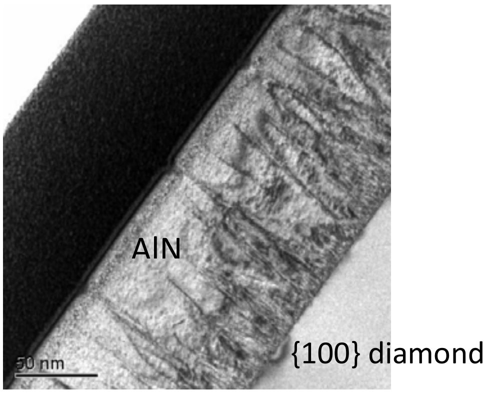


Fig. 4: *Dark field TEM image of an AlN layer grown on {100} diamond.*

Careful examination of this and similar images reveals no evidence of inversion domains (usually signified as contrast at the matrix/inversion domain boundary indicative of the displacement along 0002 of the most strongly diffracting species, in this case Al). Also apparent, is a rapid reduction in dislocation density with film thickness (to approximately 2 to 5×10^9 cm^{-2}) due to formation of threading dislocation half-loops.

CBED analysis (Fig. 5) indicates the AlN film is Al-polar (brighter fringes in the 0002 reflection). In a PEFET device, this polarity is expected to lead to a 2D electron gas (whereas N-polar AlN would lead to a 2D hole gas).

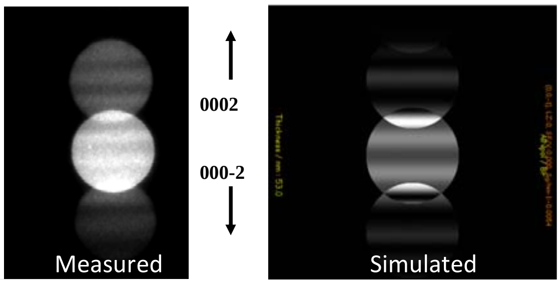


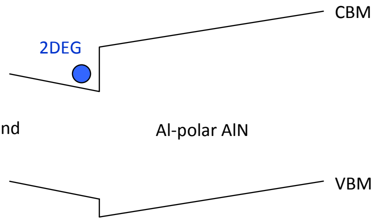
Fig. 5: *CBED image of an AlN layer grown on {100} diamond.*

Growth of AlN on {111} diamond substrates did not show domains misaligned by 30°. TEM imaging also showed no evidence of inversion domains. Similar to films on {100} diamond, a reduction in dislocation density with thickness was observed but the density was found to be an order of magnitude higher in AlN on {111} diamond compared to {100} (~10^{10} cm^{-2}). CBED measurements were inconclusive as a result of the higher dislocation density.

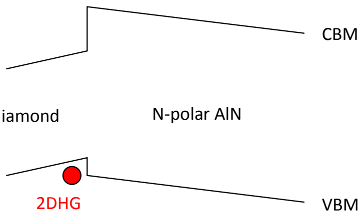
This microstructure analysis shows that, on both {100} and {111} diamond substrates, single crystal AlN can be grown with single polarity, an important prerequisite for realising a PEFET.

XPS characterisation of AlN / diamond band alignment

In order for a viable PEFET to be fabricated, in which the 2D gas is in the diamond layer, only particular configurations of band offset (the relative energies of the conduction band minima (CBM) and valence band maxima (VBM)) and AlN polarity are allowed. These configurations are summarised in Fig. 6.



2DEG requires Al-polar AlN and CBM(AlN) > CBM(diamond)



2DHG requires N-polar AlN and VBM(AlN) < VBM(diamond)

Fig. 6: *Allowed configurations of diamond/AlN band offset and AlN polarity required for a viable PEFET device.*

In order to determine the band offsets XPS was used to measure the C1s and Al2p core binding energies. In conjunction with the known energy difference between these core levels and the VBM of diamond and AlN respectively, the position of the VBM in both layers can be inferred. From this, the position of the CBM can be determined. However, due to the strong polarisation-induced electric fields, the AlN band energies, as measured using this technique, will be a function of the AlN film thickness. Therefore, the XPS measurement was repeated for a series of AlN layer thicknesses from 1 to 3 nm (Fig. 7). By extrapolating the measured energies back to zero thickness, the band discontinuities at the interface between the two materials can be estimated. This method also allows the magnitude and sign of the electric field in the AlN layer to be determined, allowing the AlN polarity to be deduced, independently of the CBED measurements.

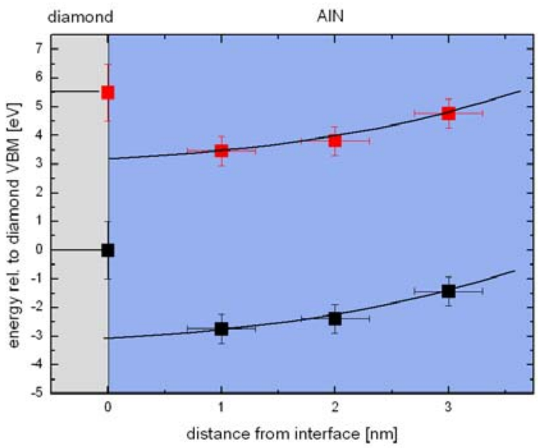


Fig. 7: *Measured band offsets between diamond and AlN.*

To within the experimental uncertainties, these band energies were measured to be the same for AlN grown on {100} and {111} diamond. The measurements show that a field of around 5 MV cm^{-1} is present in the AlN layer, in agreement with simple electrostatic calculations based on an analysis developed in [6]. Furthermore the sign of the electric field is consistent with Al-polar material, in agreement with the CBED analysis. However, the results also indicate that CBM(AlN) < CBM(diamond), which, in combination with Al-polar AlN, is not desirable as this would lead to a 2DEG in the AlN layer. This is the first time the band offsets between AlN and diamond have been reported. In the context of realising a PEFET device these results suggest further effort is required to either engineer the band offsets such that CBM(AlN) > CBM(diamond) or to deposit N-polar AlN onto diamond.

Summary

Proof of principle of surface transfer doping of diamond using a TCNQ coating has been demonstrated, The objective is to realise a stable surface conduction FET (SURFET).

AlN/diamond heterostructures have been grown using plasma-assisted MBE. Microstructure analysis shows that, on both {100} and {111} diamond substrates, single crystal AlN can be grown with single polarity, an important prerequisite for realising a PEFET device. For the first time, the band offsets between AlN and diamond have been measured and an electric field of 5 MVcm^{-1} was measured in the AlN. However, the results indicate that the combination of band offsets and polarity would lead to a 2DEG in the AlN layer. Work is on-going to either engineer the band offsets such that CBM(AlN) > CBM(diamond) or to deposit N-polar AlN onto diamond.

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