

Alternative high power RF FETs based upon CVD diamond

In this paper we review the progress made on realising the electronic material systems required for two alternative, high power RF FETs device designs based upon CVD Diamond. The first (alternative) device under consideration is an environmentally stable FET utilising transfer doping to create carriers in the diamond near surface (a SURFET); the second design is based upon an AlN/diamond heterostructure and utilises polarisation enhancement to confine carriers into the near diamond surface (PEFET). The rationale behind the various designs is described and the principle challenges of realising these novel devices discussed.

By

[C. J. H. Wort](#), [R. S. Balmer](#), [I. Friel](#) and [R. Lang](#)

Diamond Microwave Devices Ltd, King's Ride Park, Ascot, UK. SL5 8BP

Keywords: Diamond, CVD, doping, microwave, MESFET

Introduction

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 [1], may enable a real breakthrough by allowing the replacement of high power vacuum tube devices by solid-state components. If the intrinsic properties of diamond (as summarised in Figure 1) can be fully exploited through novel device design and fabrication, diamond devices could take the entire RF generation market up to 100 GHz.

CVD diamond as an electronic material

It is the unmatched combination of highest bulk thermal conductivity, high carrier mobility and high breakdown voltage that make diamond a truly multifunctional material and will allow applications in environments simply too demanding for other materials and devices. 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 regions separated from the active region of the device.

1

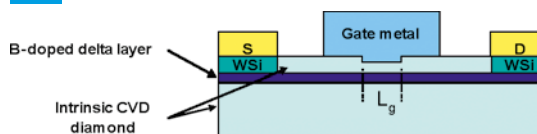
Wide bandgap	→	High temperature
High thermal conductivity	→	High power
High breakdown field	→	High voltage
High carrier mobility and saturation velocity	→	High frequency
High bond strength	→	Radiation hard

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

Delta-doped MESFET for high power, high frequency applications

Currently under development at DMD is the delta-doped FET design (as shown in Figure 2) which achieves a degree of separation between the holes and ionised acceptors by incorporating a ultra-thin 'delta' doped 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 10^{20}cm^{-3} would be $< 1\text{cm}^2\text{V}^{-1}\text{s}^{-1}$, whereas it could potentially be as high as $3800\text{cm}^2\text{V}^{-1}\text{s}^{-1}$ in the intrinsic regions. Quantum-mechanical calculations 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 [2].

2



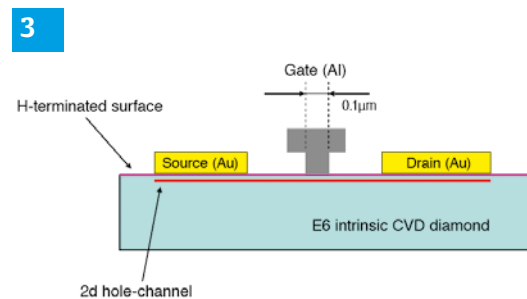
Delta-doped FET design.

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.

Devices that can more properly use the exceptional intrinsic properties of diamond are obviously attractive and two such concepts are discussed below.

Surface conduction FET (SURFET)

This hydrogen surface termination possible on diamond causes a 2-dimensional hole channel to form in the diamond layer several nanometers below the surface. The exact mechanism leading to the formation of this hole-channel is still under debate; however, it is believed that atmospheric contamination, especially the condensation of water-vapour onto the hydrogenated diamond surface (forming a redox couple in which electron transfer from the diamond into a suitable molecule is promoted), plays a key role in creating the conductive channel below the surface [3]. During FET operation, holes travel through this channel from the source contact to the drain contact near the surface. Modulating the gate voltage changes the hole conduction, making FET operation possible.



Schematic design of a surface FET.

Current surface conduction FET devices fabricated by NTT on E6 diamond substrates [4], have demonstrated encouraging high frequency and power performance with power densities up to 2W/mm recently reported in the literature. However, such devices are not environmentally stable. This is due to the choice of surface adsorbates (water vapour) to achieve transfer doping within the diamond near surface.

It was recently report by Erlangen University [5], that certain Fullerenes can be used to achieve the required transfer doping in diamond (which occurs provided the Fermi level in diamond is higher than the Fermi level in the surface layer then we achieve transfer doping to the lowest unoccupied molecular orbital – LUMO). The reported mobility of $<80 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$ places significant challenges on the device design and fabrication to extract practical performance; however, this could be due to a defective diamond sub-surface and innovative technology to produce surfaces on diamond with a very low sub-surface defect density are being supported by DMD at E6.

DMD is currently working with Oxford Advanced Surfaces (OAS) to identify alternative surface moieties that not only induce surface conduction but also provide environmental stability. It is hoped that through engineering of the diamond surface (which must also be basically defect-free) efficient transfer doping is achieved and the resulting FETs produced are environmentally stable.

The challenges are summarised thus:

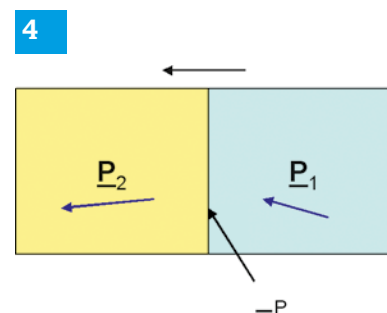
- Realising a low defect diamond surface and sub-surface: DMD is working with E6 to provide suitable electronic grade material.
- Identifying and providing a surface treatment that induces time-stable transfer doping: DMD is working with OAS to design and engineer suitable organic molecules that allow transfer doping.
- Fabricating a SURFET once a stable surface modification has been achieved.

Polarisation enhanced FET (PEFET)

The PEFET concept is based on using polar materials and a hetero-interface to create separation of carriers from acceptors and carrier confinement in a 2D gas as the basis of a high mobility transistor.

When two polar dielectric materials with polarization P_1 and P_2 are joined together, as shown in Figure 4, a polarization sheet charge is formed at the interface given by:

$$\sigma P = -(P_2 - P_1) \cdot \hat{n}$$

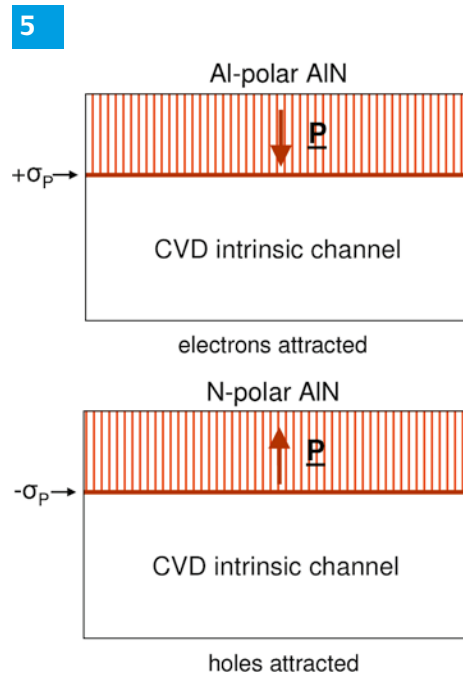


Showing sheet charge generation at the interface between two different dielectrics.

Assuming layer 1 to be the diamond layer and layer 2 to be the polar material we have $\sigma_P = -P_n$, where P_n is the component of polarization normal to the interface between the two materials. This sheet charge gives rise to an electric field in the diamond layer of $E \approx -P_n/2\epsilon_0\epsilon_{\text{diamond}}$ (assuming an infinite 2D sheet charge with no compensating free charges).

Taking AlN as an example of the polar material ($|P_{\text{AlN}}| = 0.081 \text{ C m}^{-2}$; $\epsilon_{\text{diamond}} = 5.57$) yields an electric field in the diamond layer of $|E| \sim 8.2 \text{ MV cm}^{-1}$. The direction of this electric field depends upon the polarity of the AlN layer.

For Al-polar material the sheet charge is positive and therefore holes would be repelled from the interface; for N-polar material the sheet charge is negative and therefore holes would be attracted. This is illustrated in Figure 5 below:



Showing affect of polarisation direction.

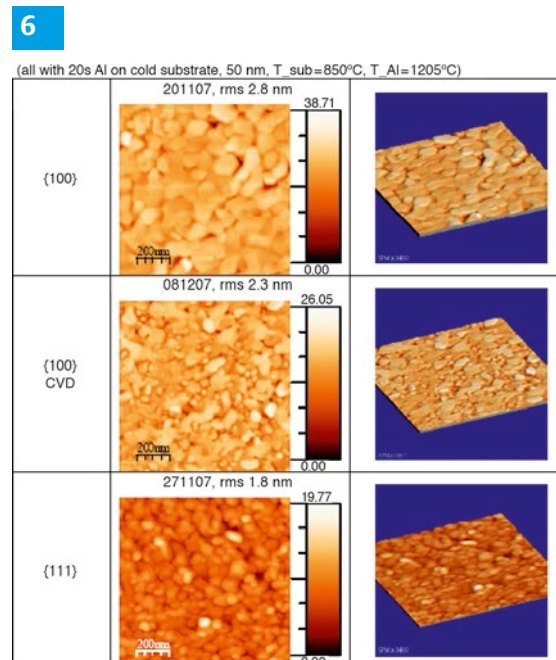
The charge carriers can be either holes or electrons. Such a structure is analogous to the AlGaIn/GaN HFET design and thus the basic concept is well-proven. The distinction here is that, unlike AlGaIn/GaN, diamond does not form a solid solution with a polar material, but conceptually neither this feature nor indeed heteroepitaxy at the interface, is actually necessary for device operation.

The device design does require further innovation and R&D in:

- Controlling the polarity of the polar layer and DMD are working with the Walter Schottky Institute to realise suitable AlN on diamond layers.
- Device fabrication and testing, once the PEFET material layers have been formed.

Results on PEFET material realisation

Figure 6 shows that AlN can be grown epitaxially onto both (100) and (111) diamond surfaces by MBE, with better nucleation and layer quality being obtained on the (111) surfaces.

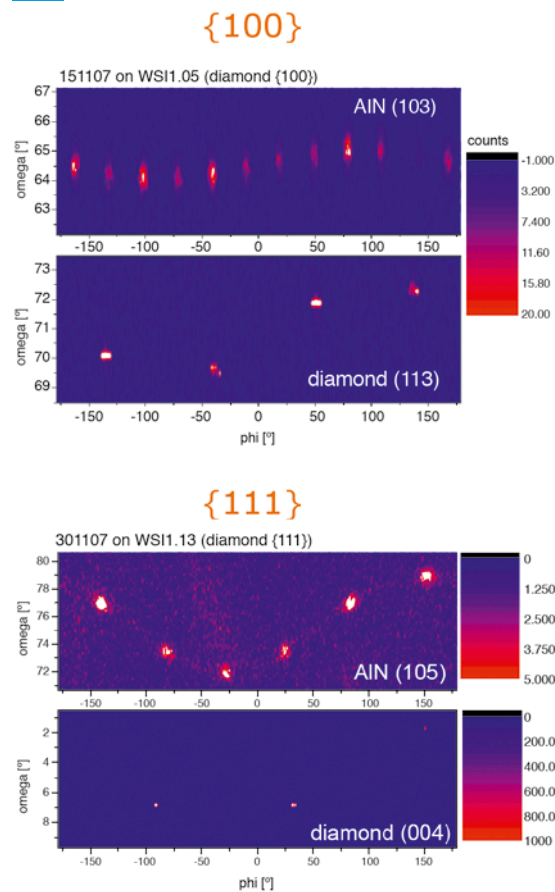


AFM images showing 50nm layers of AlN grown onto various diamond surfaces.

The smoothest surfaces are obtained from (111) substrates and growth onto (100) CVD diamond surfaces leads to domains of multiple sizes.

Figure 7 Shows Pole figures of AlN grown onto (100) and (111) diamond surfaces. Note: {100} films the (103) reflection exhibits 12-fold symmetry (6-fold expected). This is due to the presence of two hexagonal domains misaligned by 30°. On {111} films: the (105) reflection exhibits 6-fold symmetry (as expected). The "S-shape" is due to sample misalignment and miscut.

7



Showing epitaxial relationship between AlN and diamond.

Summary

The extreme properties of diamond make single crystal CVD diamond an attractive material for high power and high frequency electronic device applications. Diamond Microwave Devices Ltd (DMD) is developing novel, diamond-based material systems, structures and device fabrication processes in order to achieve a high performance diamond microwave transistor.

In addition to the delta-doped device development, DMD is also expecting to fabricate prototype SURFET and PEFET devices during the EMRS/DTC funded programme with the intention to then benchmark these against the delta-doped devices.

Progress towards realising a device with RF performance has encountered several significant technical challenges, however, recent developments indicate an encouraging future for diamond electronics.

Acknowledgements

The work reported in this paper was funded by the Electro-Magnetic Remote Sensing (EMRS) Defence Technology Centre, established by the UK Ministry of Defence and run by a consortium of SELEX Galileo, Thales UK, Roke Manor Research and Filtronic.

DMD also wish to acknowledge the contribution and support from Element Six Ltd, Walter Schottky Institute and Oxford Advanced Surfaces.

References

1. J. Isberg, J. Hammersberg, E. Johansson, T. Wikstrom, D.J. Twitchen, A.J. Whitehead, S.E. Coe, G.A. Scarsbrook, *Science* **297**, 1670–1672 (2002).
2. A. Denisenko. Private communication, Nov. (2006).
3. K. Ueda, M. Kasu, Y. Yamauchi, T. Makimoto, M. Schwitters, D.J. Twitchen, G.A. Scarsbrook, S.E. Coe, *IEEE Electron Device Letters*, **27**, 570 (2006).
4. Angus paper.
5. Lothar Ley C60 paper.