Diamond
A New Materials Base for Future Ultra High Power RF Electronics

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Abstract

Diamond is an ideal semiconductor material for high power / high temperature electronic systems with active device structures and MEMS components. Despite the difficult materials and device technology, individual transistor structures and passive components have been realized, allowing to extract first encouraging microwave performance data. A critical issue is still the availability of single crystal substrates. The state of the art of both groups of devices (active and passive) is reviewed together with the materials requirements for ultra high power RF applications.

INTRODUCTION

Diamond is an interesting material for many industrial applications. In many areas its properties are extraordinary like its mechanical hardness and fracture strength, its high stiffness (Youngs modulus), its high thermal conductivity and its large bandgap of 5.45 eV [1]. Thus, in electronics it may be an ideal material for ultra high power applications with the potential to outperform devices and circuits based on other wide bandgap semiconductors. However, the possibilities of doping are severely restricted. In addition it lacks a natural substrate of noticeable size. This has complicated the development of electronic device structures, which had to be unipolar p-type and had to be realized on small size single-crystal chips. High performance MEMS structures have generally been realized on poly-crystalline or nano-crystalline CVD material and passive RF components on diamond could well complement high power / high temperature active device structures.

Recently, some important breakthroughs have been achieved, like an electron mobility of 4500 cm^2/Vs and hole mobility of 3800 cm^2/Vs [2], shallow n-doping through deuteration of boron (acceptor) [3] and single crystalline CVD substrates of $1 cm^2$ surface area [4]. Although these features have not been implemented into device structures yet, recently it has been possible to fabricate diamond surface-channel FETs with cut-off frequencies in the GHz-range together with first power and noise measurements [5]. Passive components like mechanical resonant filters and microwave switches have been realized on micro- and nano-crystalline material grown on Si [6,7]. The individual performance data may allow already to estimate the power handling capability of diamond semiconductor circuits.

SUBSTRATES AND DOPING

Synthesis of diamond single crystals is obtained only at high temperature and pressure even when using catalysts (HPHT-crystals). Still these crystals are small in size and contain a large number of defects.

On the other hand CVD films can be grown at moderate temperatures (approx. 800 °C) using CH_4 as precurser in hydrogen. Semiconductor grade layers are usually grown by microwave plasma assisted CVD on 100-oriented chips cut from HPHT crystals or selected natural stones. Such layers can be separated from their substrate and have yielded in the record mobilities as mentioned above. With high lateral growth rate the chip size can be expanded to approx. $1 cm^2$. Wafers with 1” diameter are expected by the end of this year.

In a different approach single crystal quasi-substrates have been grown on Ir, which had been deposited onto $SrTiO_3$ [8]. Due to the lattice mismatch and the thermal mismatch, the film may detach from the template after cooling. The mismatch problem has limited the size of these free standing quasi-substrates to approx. $1 cm^2$ up to now.

The third class of materials are poly-crystalline films and nano-crystalline films mainly grown on 100-oriented Si-wafers. The properties of the films vary. While the mechanical properties are widely maintained, the thermal conductivity and the electronic properties are largely influenced by grain boundary defects. Fig. 1 gives an impression of currently available substrates.

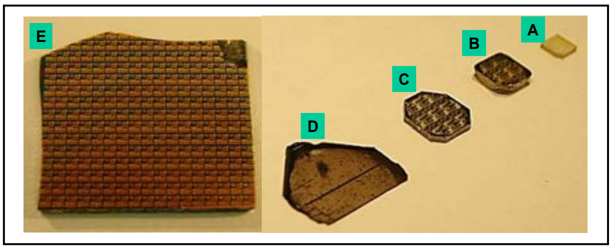

FIG. 1:
Diamond substrates used for FETs. (A) 111-oriented HPHT crystal, (B) 100-oriented HPHT crystal, (C) CVD single crystal substrate (Apollo Diamond), (D) quasi-substrate grown on Ir/SrTiO$_3$, (D) nano-diamond chip cut out of a 4” diameter wafer.

Doping is restricted to a few elements, namely B, N and P. All dopands are deep. Boron is an acceptor with E_A = 0.37 eV, which is only reduced for concentrations above 10^{19}cm^{-3} due to miniband formation. N and P are donors with an activation energy of 1.7 eV and 0.62 eV respectively. P has only been successfully incorporated on donor site using the 111-growth direction. Recently, n-doping with E_D = 0.23 eV has been reported by double deuteriation of boron acceptors. However, the boron acceptor is still the workhorse for active layers up to now. In addition to boron, the hydrogen terminated surface displays a p-type conductivity in a surface near 2DHG-like channel with a sheet charge density of approx. 10^{13} cm^{-2}.

For RF power electronics this leaves two options for the design of the p-type channel devices: narrow boron delta doping of only a few monolayer thickness [9] and the hydrogen-induced surface channel, generated without external doping [10]. Both avenues have been explored.

FET DEVICES

Using the hydrogen-induced 2DHG-like channel, offers the possibility of an FET technology without extrinsic doping. Although the nature of this channel configuration and especially the nature and location of the intrinsic acceptor are still under discussion, this configuration has been successfully used to fabricate planar high speed FET structures. MISFETs with CaF$_2$ gate insulator and employing a spacer technology have been realized [11] as well as MESFETs with self-aligned T-gates [12].

Such surface-channel MESFETs have been realized on a variety of substrates as listed in fig. 1. In all cases the FETs were enhancement mode with low leakage. However maximum current densities and mobilities depend essentially on the materials configuration. While FETs on high purity buffer layers have yielded open channel current densities up to 360 mA/mm (for L_g = 0.2 µm), devices on nano-diamond show drain currents of µA/mm similar to TFTs in other materials.

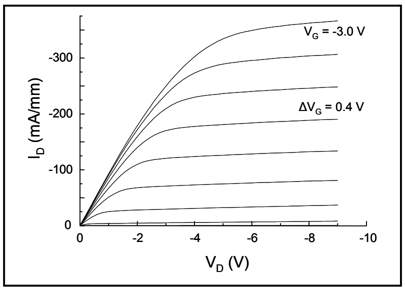

FIG. 2:
Output characteristics of surface-channel MESFET with 0.2 µm gate length, (after [13]).

On unintentionally doped buffer layers with high hole mobility (1200 cm^2/Vs) the surface channel mobility is still only approx. 150 cm^2/Vs, presumably due to surface scattering. However, at low current levels excellent cutoff frequencies could be obtained for L_g = 0.2 µm: f_T = 25 GHz, $f_{max\ MAG}$ = 63 GHz and $f_{max\ U}$ = 81 GHz. At the same gate bias point a minimum noise figure of NF = 0.72 dB at 3 GHz has been extracted. These are the highest cutoff frequencies and the first microwave noise measurements obtained with diamond FETs up to date [13].

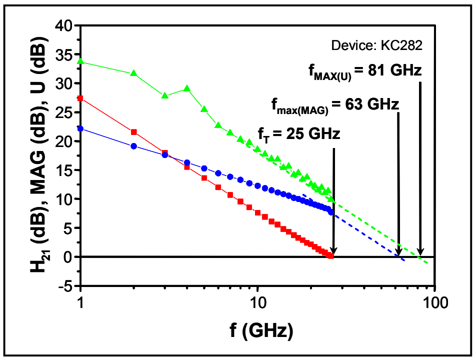

FIG. 3:
Cutoff frequencies of surface channel FET (L_g = 0.2 µm , W = 200 µm) extracted from s-parameter measurements between 3 and 26 GHz, bias point V_D = -20 V, V_G = -0.3 V (after [13]).

Diamond is not a polar material and polarization induced charge instabilities are not expected. Nevertheless, the hydrogen-terminated surface is free of surface states within the bandgap and the surface potential unpinned. However it can be stabilized by chemical treatments and in large signal operation no current compression or power slump is observed. First power measurements on short gatewidth devices at 1 GHz have yielded in a saturated power density of 0.35 W/mm in class A operation, this number however being limited by incomplete matching. It represents one of the first RF large signal power measurements of a diamond FET structure [13].

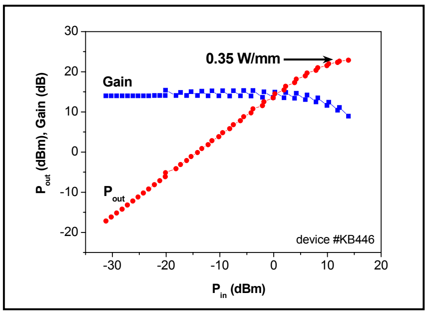

FIG. 4:
Class A power plot at 1 GHz, (L_g = 0.4 µm, W = 550 µm) bias point V_D = -20 V, V_G = -2.0 V, (after [13]).

These transistor structures are still experimental. Higher cutoff frequencies above 100 GHz are expected, when channel mobilities can be improved. Higher output power is expected, if the simple self-aligned gate technology is refined and field plate concepts can be implemented. It seems most likely that this will require a better controllable channel configuration based on boron delta doping.

Such delta-doped channel structures have also been explored [12]. High precision in growth is needed. To illustrate this, fig. 5a shows a delta-profile with negligible activation energy (requiring a peak concentration of 10^{20} cm^{-3}). The mobility within the spike is low (in the order of 10 cm^2/Vs), but may be close to the buffer layer bulk mobility adjacent to the spike. In the case shown, 88% of the carriers reside outside the doping spike and the bulk mobility will only be marginally degraded. The steepest delta doping profile realized to date on a buffer layer on an HPHT crystal is shown in fig. 5b. This profile contained a sheet charge density of 4.4 x 10^{13} cm^{-2} and could therefore not be fully depleted in the FET structure. Schottky diodes on such delta profiles show high leakage currents. Thus, the concept of a diamond delta-channel power FET is clear, the technological window however extremely tight. The technological realization hinges still on refinements in monolayer growth, recess etching, substrate quality, substrate availability and wafer area.

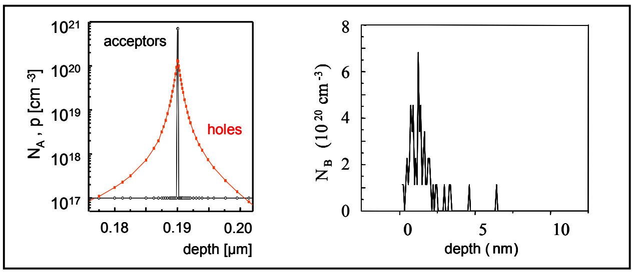

FIG. 5:
Left: 3 monolayer delta doping with 10^{13} cm^{-2} sheet charge density and hole distribution.
Right: ERD boron doped delta profile with FWHM = 0.9 nm, peak N_A = 7 x 10^{20} cm^{-3}, integrated sheet charge 4.4 x 10^{13} cm^{-2}; Measurement by A. Berghammer, G. Dollinger (TU Munich).

Nevertheless, taking the best data of individual building blocks already realized a classical power FET structure may be simulated (fig. 6). This has resulted in an RF power limit of 27 W/mm. Into this calculation a large number of materials data structural data and boundary conditions have entered. For details the reader may be referred to the literature [12]. The essential data are a sheet charge density of 1.3 x 10^{13} cm^{-2}, a breakdown field of 10 x 10^6 V/cm, a channel mobility of 1000 cm^2/Vs and a saturated velocity of 1.0 x 10^7 cm/s. The nitrogen deep donor in the shield and gate layer will not be activated. In the gate this will result in a lossy dielectric barrier. The surface is oxygen terminated, which results in surface potential pinning at 1.7 eV above the valence band edge and an associated surface depletion.

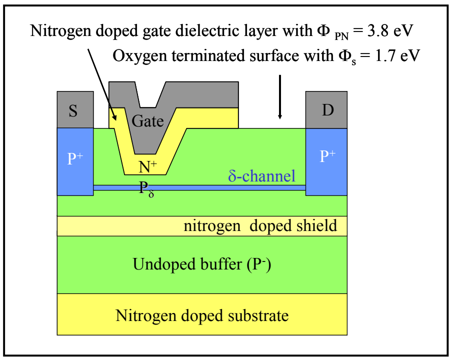

FIG. 6:
Cross section of delta-channel FET with recess and field plate, details see text, (after [12]).

This calculation has then been taken further to calculate the thermal loading on a chip of 4 mm x 4 mm size with an FET with 4 mm total gate width. On such a chip 100 W RF power may be generated at a channel temperature of approx. 240 °C. This temperature seems high, but may be compared with the operation of a diamond Schottky diode at 1000 °C (in vacuum) using a refractory metal contact [14].

MEMS

A high mechanical resonance frequency (due to the high Young's Modulus), high thermal stability (no plastic range) and high thermal conductivity make diamond an interesting material for RF MEMS. Indeed, 640 MHz resonance frequency have been obtained with cantilever bridges [6] and diamond mechanical switches have operated at 650 °C in vacuum [15].

In our laboratory we have concentrated on RF switches in coplanar arrangement as used in radar front ends, transmit and receive modules etc.. Often, these are cantilevers operated electrostatically like the lateral switch shown in fig. 7. In this technology the entire structure is fabricated in diamond on a diamond template (on Si), except for the final metallization. Transission loss and isolation are shown in fig. 8. The advantage is (among others) operation at high temperature allowing to switch very high power densities without contact sticking problems. The disadvantages are high switching voltages and low switching force.

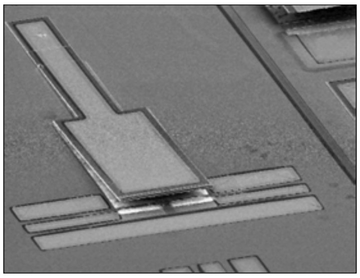

FIG. 7: Lateral diamond cantilever switch with electrostatic drive. The length of the coplanar line is 1.5 mm, (after [15]).

An alternative is the electrothermal drive (bi-metal effect). Diamond has a low thermal expansion coefficient and can well be combined with refractory metals like Ni. Cantilevers and bridges using this principle have indeed been designed, built and operated with driving voltages as low as 1.3 V [16]. The problem to hold the switch in two stable positions without standby power can be solved by using bi-stable conditions based on pre-stressed films.

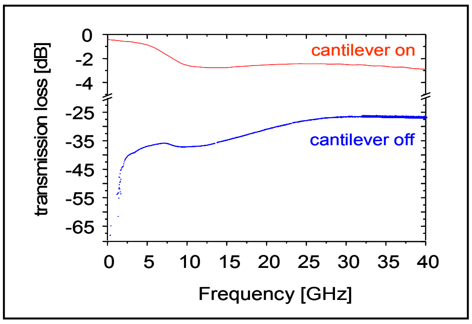

FIG. 8: transmission loss and isolation of lateral switch as shown above. In the measurement the switch was operated mechanically

PERSPECTIVE AND CONCLUSION

Diamond is indeed a challenging material for high power / high temperature electronics. Proof of concept experiments allow already to highlight some of the advantages in comparison to other wide bandgap materials. The main hurdle seems to be the lack of high quality substrates of relevant size. Here promising attempts are under way. However, the full potential may only become visible once heterostructures with other wide bandgap materials (in their cubic phase) like AlN and BN are developed. Diamond is an ideal substrate for active amplifier devices as well as passive components. With advances in materials development diamond may emerge as an ultimate materials base for ultra high power solid state amplifiers at microwave frequencies well beyond 100 GHz.

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ACRONYMS

CVD : chemical vapour deposition
2DHG : two dimensional hole gas
ERD : electron recoil detection
HPHT : high pressure high temperature
MESFET:metal semiconductor field effect transistor
MISFET : metal insulator field effect transistor
TFT : thin film transistor