Diamond for
High Power / High Temperature Electronics

E. Kohn, M. Kubovic, F. Hernandez-Guillen, A. Denisenko

Dept. of Electron Devices and Circuits, University of Ulm, D-89081 Ulm, Germany
e-mail: kohn@mailix.e-technik.uni-ulm.de, phone: +49 731 50 26151

Abstract - **Diamond is a wide bandgap semiconductor with extremely attractive properties but also many technological difficulties. Doping is restricted to deep impurities and substrate size is very limited. Nevertheless in proof of concept experiments, the potential for high power, high temperature and high frequency applications can already well be estimated. In addition, first passive MEMS elements for advanced circuit applications have also been demonstrated, however still on nano-crystalline material, which is available with large surface area. Thus it is already possible to discuss an integrated systems approach when single crystal substrates in wafer size become available.**

I. INTRODUCTION

Diamond is a material with many extraordinary properties like its mechanical hardness and fracture strength, its high stiffness (Youngs modulus), its chemical inertness, its high thermal conductivity and its large bandgap of 5.45 eV. Its semiconducting properties have been identified in the early 1950's using natural stones, but the use as active semiconductor material has been severely restricted due to the limited possibility of doping and the small substrate dimensions. However, recently, some important breakthroughs have been achieved, like an electron mobility of 4500 cm^2/Vs and hole mobility of 3800 cm^2/Vs [1], shallow n-doping through deuteration of the boron acceptor [2] and single crystalline CVD substrates of 1cm^2 surface area [3]. Several configurations have been used to obtain diode operation at around 1000 °C in vacuum [4,5]. Microwave FET devices have reached cut-off frequencies up to 80 GHz now [6]. Yet, in another materials configuration labeled NCD (nano-crystalline diamond) and UNCD (ultra-nano-crystalline diamond) deposited as thin films on Si-substrates, a number of MEMS device structures have been demonstrated including resonators and RF switches [7,8]. It seems that these two materials configurations are two different worlds and monolithic integration of active device structures and passive circuit components seems not realistic at present. However, this may change with quasi-single crystal films, which can be deposited on Ir, and which in turn are deposited onto Si including intermediate stress release layers [9]. All prerequisites seem therefore to exist, making diamond a full range electronic material for ultra high power and ultra high temperature electronics.

II. DIAMOND PROPERTIES

Diamond single crystals are usually grown in a high pressure high temperature synthesis (HPHT) cycle at the stability limit of the diamond phase. Such crystals are small in size and contain a large number of defects.

On the other hand diamond can also be synthesized within the methastable region at moderate temperatures (approx. 800 °C) using CH_4 as precursor in hydrogen by chemical vapour deposition (CVD). 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 mobilities for electrons and holes of μ_n = 4500 cm^2/Vs and μ_p = 3800 cm^2/Vs 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 next year. Fig. 1 gives an impression of currently available substrates.

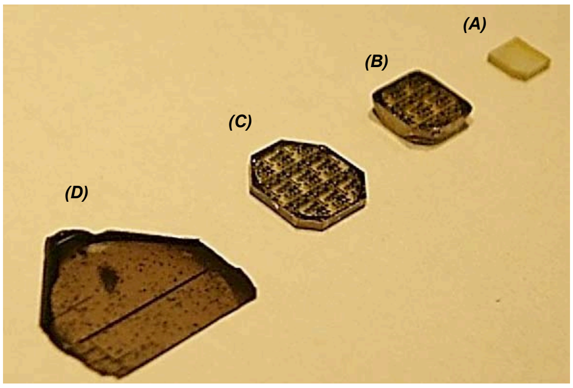

Fig. 1:
Diamond substrates: (A) 3x3 mm^2 111-oriented HPHT crystal, (B) 100-oriented HPHT crystal, (C) CVD single crystal substrate (supplied by Apollo Diamond), (D) quasi-substrate grown on Ir/$SrTiO_3$ (grown by M. Schreck, University of Augsburg, Germany).

In a different approach single crystal quasi-substrates have been grown on Ir, which had been deposited onto $SrTiO_3$ [10]. 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 free standing quasi-substrates to approx. 1 cm^2 up to now. The third class of materials are polycrystalline films and nano-crystalline films mainly grown on 100-oriented Si-wafers. The properties of such films vary. While the mechanical properties are widely maintained, the thermal conductivity and the electronic properties are largely influenced by grain boundary defects.

III. DOPING of DIAMOND

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 [2]. The boron acceptor is still the workhorse for active layers up to now. In addition, 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} [11]. The doping capabilities are shortly summarized in fig. 2.

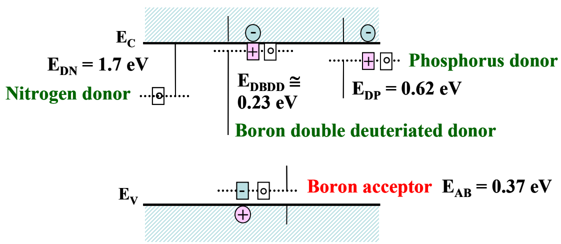

Fig. 2:
Diamond donor and acceptor doping configurations.

For RF power electronics this leaves two options for the design of the p-type channel devices: narrow boron delta doping of high peak concentration and only a few monolayer thickness [12] and the hydrogen-induced surface channel, generated without external doping. Both avenues have been explored.

IV. DIODE STRUCTURES

In the line of technological complexity diodes contain a junction in addition to resistive parts and ohmic contacts. Such structures are sensitive to surface conditions, deep centers and the thermal stability of the materials system. Of specific interest here may be the defect properties and thermal stability. Both can be extracted from temperature dependent IV and CV characteristics. Due to the high bandgap, intrinsic carrier concentrations are low; for example even at 1000 °C it is only in the same order as that of Si at R.T. Thus, if the chemical stability is sufficient, very high temperature operation should be possible. Diamond is a metastable phase of carbon and graphitization will occur at some point. However, graphitization in the crystal is not observed below 1500 °C; and it has been shown that the diamond phase can "survive" 2200 °C in pure H-atmosphere [13]. But what is observed electronically? Schottky diodes with refractory junction contacts have indeed been fabricated and tested up to 1000 °C in vacuum (to prevent burning) [4]. Operation at 1000 °C has been demonstrated however, only for a short period of time before catastrophic failure occurred. It was speculated that the Schottky metallization finally starts to interact with diamond forming a carbide interface. Already at medium temperatures, high reverse current leakage could be observed. It was suggested that the entire leakage current had been generated by interfacial defects.

Recently, a novel junction structure has been investigated, which only contains carbon. In this structure an n-type doped ultra-nano-diamond film (UNCD) was deposited onto a lightly boron doped active layer on a highly doped contact layer, grown on a single crystal diamond HPHT substrate comparable to the sample (B) shown in fig.1. The UNCD film technology has been developed at Argonne National Laboratories by D. Gruen and the film had been deposited in his laboratory. UNCD contains a high amount of grain boundaries and doping with high concentrations of nitrogen results in n-type conductivity with high activation [14]. In such heterostructures carbide formation should not occur. Thus. high temperature operation should be more reliable. Indeed, first experiments showed no degradation or destruction in a sequence of several experiments ramping the temperature up to 1050°C. Such a characteristic is shown in fig. 3.

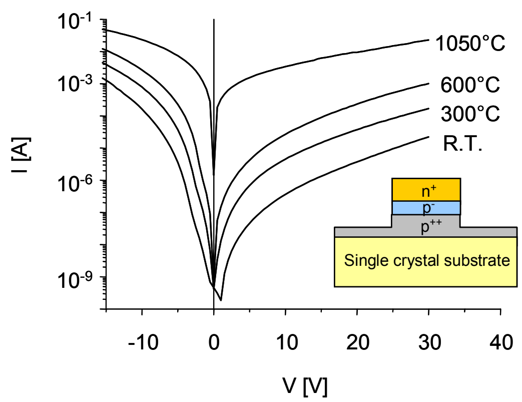

Fig. 3:
Diode IV-characteristics between R.T and 1050 °C for a pn-structure as described in the text.

Also seen in fig. 3 is a high thermally activated reverse leakage current generated by defects, limiting the on/off current ratio. The current in the forward direction increases due to the boron acceptor activation. This effect may be reduced by incorporating the delta doping concept as briefly introduced above.

V. FET DEVICES

FET device structures require full doping activation in the channel at the operating temperature. The channel requires therefore a delta doping profile with high peak concentration. In addition a power FET design needs to include a gate recess (to access the full channel sheet charge density even in the case of surface depletion) and a field plate (to eliminate field spikes in the structure causing premature breakdown). This may be illustrated in figs. 4a and 4b, where a planar delta doped channel device structure is contrasted with a recessed gate field plate structure, searching for a suitable configuration for maximum RF output power.

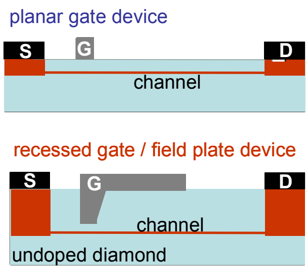

Fig. 4a :
Schematic cross section of plana rand recessed gate devices with field plate as used in fig. 4b.

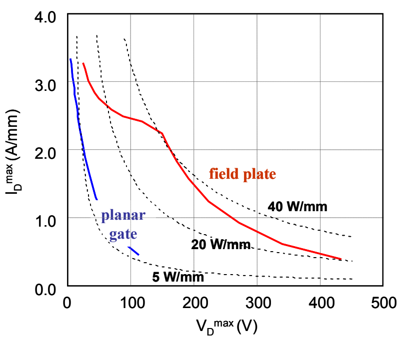

Fig. 4b :
Comparison of RF power handling capability for planar FET device and recessed gate structure with field plate. Data are state-of-the-art or ideal. Operating temperature is assumed at 20 °C. After [15].

In the 2D-simulation experimentally determined materials parameters have been used, if availabe. Not available still is the saturated velocity reached at high fields (assumed to 1.0 x 10^7 cm/s). Surface and Schottky barrier height are 1.7 eV (O-termiation). As can be seen, a planar device structure is not attractive. However, recess and field plate optimization may result in very high power densities up to 40 W/mm. In addition, on diamond the device will contain an integrated heat spreader, allowing also high output power at large gatewidth. In combination with the high temperature diode measurments, this implies that the structure would also be able to tolerate high channel temperatures under operation, possibly also extending the reliability. Experimental verification of these predictions is however still outstanding.

Nevertheless, microwave performance of FET structures has been demonstrated, however in a different configuration. Here a delta channel has been implemented which has been induced by the hydrogen termination of the surface. In this case no extrinsic doping is introduced and an acceptor level generated at or beneath the surface by the hydrogenation process itself. Although the physical/chemical details of this configuration are not yet fully understood, devices have been successfully realized based on this concept. Although the channel mobility measured is still low (approx. 150 cm^2/Vs) operation at microwave frequencies has been shown with cut-off frequencies f_T = 24 GHz and f_{max} = 80 GHz for a gatelength of 0.2 µm, see fig. 6. The experimental technology allowed also first power and noise measurements. A minmum noise figure of F_{min} = 0.72 dB has been measured at 3.0 GHz and a saturated output power of 0.34 W/mm at 1.0 GHz. The extracted power density is still more than an order of magnetude below expectations. Thus, the experiments need still to be considered as proof of concept experiments.

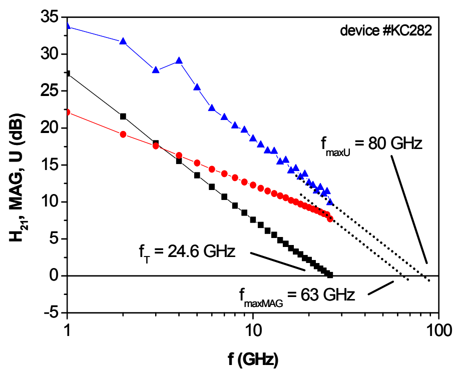

Fig. 5:
Cut-off frequencies of surface channel FET with L_g = 0.2 µm extracted from s-parameter measurements between 1.0 GHz and 26 GHz, bias point V_D = -20 V, V_G = -0.3 V, after [6].

VI. RF-MEMS

Nano-crystalline diamond has already been introduced as a new carbon materials configuration used in the ultra high temperature stable diode structure. It can be deposited by microwave plasma CVD or hot filament CVD onto large area substrates like 4” or 6” diameter Si wafers. Based on this material a variety of microsystems technologiy processes have been realized including dry etching, boron doping, sacrificial layer etching etc.. Related to electronics, demonstrated have been heat spreaders, all diamond packages, resonators with GHz resonance frequencies and RF switches [8,16,17].

Important materials parameters here are a high mechanical resonance frequency (due to the high Youngs Modulus), high thermal stability (no plastic range) and high thermal conductivity.

As an example, in fig. 6 a switch in a bridge configuration is shown, which is switched between two bi-stable positions using bi-metal thermoelectric actuation [7]. In this case specific stress engineering is needed to pre-stress the bridge with a certain displacement.

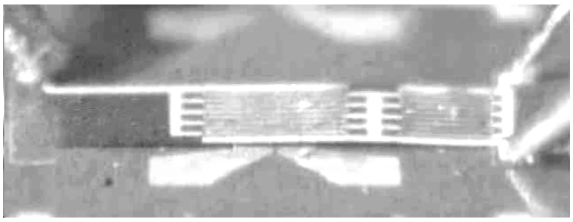

Fig. 6:
All-diamond bi-stable double anchored microswitch with bi-metal actuation. Beam length 1.5 mm. After [7].

The structure is still basic has thus not been optimized for RF operation yet and has not yet been integrated into a co-planar arrangement. Earlier versions have been based on electrostatically driven single anchored cantilevers and have operated up to 650 °C in vacuum without change in threshold voltage, indicating no change in Youngs modulus and internal stress. Such devices have also been operated at microwave frequencies with high insertion loss and isolation [9].

VII. CONCLUSION and OUTLOOK

Despite of serious restrictions in doping, it is possible to demonstrate the high power / high temperature capability of diamond as active electronic material. It can indeed be expected that diamond diodes and field effect transistors can operate beyond the the limits of other wide bandgap semiconductors. High RF power densities may be optainable with values as high as those expected for GaN based heterostructures. However, the built-in heat spreader may allow also high output power operation under CW conditions.

Heterostructures have not yet been implemented into diamond and are still one of the main challenges ahead. Other challenges are certainly the search for a shallow chemically stable donor. From the materials point of view the advancement for larger substrate areas beyond 1 cm^2 is very encouraging so that it is quite likely that the RF MEMS structure, which are now only being realized on nano-diamond, could be monolithically integrated into ultra high power MMICs containing an integrated heat spreader.

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