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Advances in diamond surface channel FET technology with focus on large signal properties

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Abstract

Field effect transistors based on a hydrogen induced p-type surface channel (surface channel FETs) have shown steady progress in the past. Devices with sub-µm gatelength have been fabricated and cut-off frequencies up to the mm-wave range could be extracted. However, large signal and power performance could only be reported recently. This is due to severe stability and degradation problems. These phenomena are largely related to the highly polar H-terminated diamond surface, although details are still in discussion. This contribution describes these instabilities and the recent progress obtained. To some extent this may also shine some light onto the nature of instabilities observed in GaN based devices.

1. Introduction

The hydrogen terminated diamond surface induces a p-type channel of high carrier density (with an $N_{s,p}$ in the range of 10^{13} cm^{-2}) in close proximity to the surface [1]. This channel has been analyzed in detail down to low temperatures and identified as hole accumulation layer and 2DHG with activation energy below 23 meV [2]. The nature of the related acceptor is still in discussion and several models have been put forward either proposing acceptor surface states or doping transfer from adsorbates [3, 4]. The surface itself is highly polar due to the strong dipole moment of the surfacial H-C bond (fig. 1) and un-pinned in respect to the Schottky barrier of metal contacts [5]. Thus, ohmic and Schottky contact behavior can be realized using metals of different work function. This configuration has been used for the fabrication of Schottky-gate FETs [6, 7] and metal-insulator-gate FETs with various insulators like SiO_x, CaF_2 and BaF_2 [8-12].

On the other hand, terminating the diamond surface by oxygen, results in a highly insulating surface due to a surface potential pinning at 1.7 eV above the valence band [13]. This property has been used to obtain localized active device areas (by employing an oxygen plasma treatment).

The characteristics of the Schottky-gate FETs can well be fitted to HFET or MOSFET models, based on a gate barrier separation layer of 5 to 10 nm [14-17]. This leads to the hypothesis of a hydrogen induced sub-surface channel, a surface barrier layer and a high surface state density acting as surface acceptor (see fig. 2). The surface hydrogen is positively charged, with most of its electronic charge being transferred to the carbon atom below. This will attract negative charges to the surface, change the overall vertical charge balance and influence the 2DHG channel density.

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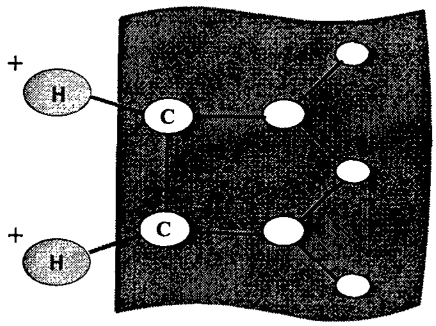

Fig. 1. Surface H^+C^- dipole on (100) diamond surface.

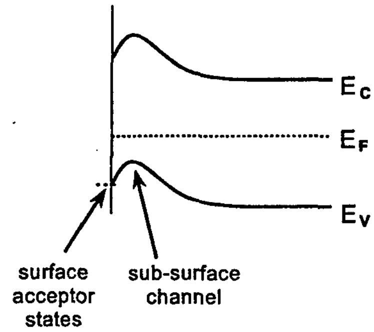

Fig. 2. Proposed energy band diagram of H-terminated diamond surface.

Sub-μm technologies have been developed for both, Schottky-gate FETs and MISFETs with self-aligned T-gates. The Schottky-gate FET devices were unpassivated, MISFET devices used CaF_2 as gate dielectric and an overlapping gate configuration. These technologies were applied to single crystal synthetic HTHP substrates of chip size approx. 4 mm x 4 mm. Equivalent circuit models have been developed and cut-off frequencies in the GHz-range extracted [16, 18, 19]. The high-speed small signal performance could be scaled down to 0.2 μm gatelength (see fig. 3) [18]. However, attempts to measure the large signal properties have failed largely. The devices degraded during the measurement at high current and bias levels. Only one attempt of operation in class B has been published [16].

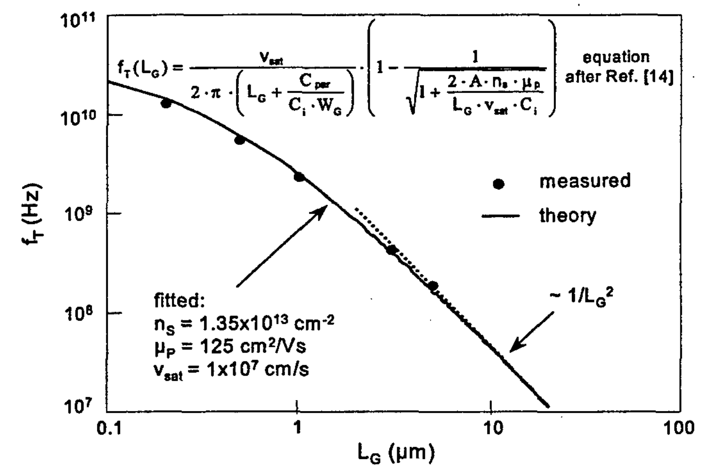

Fig. 3. Measured and calculated f_T dependence on L_G, after Ref. [12].

At the same time, it was found that the hydrogen terminated diamond surface is pH-sensitive in the liquid environment [20], where the pH-value defines the electrochemical potential of the solution. This again was expected since the surface is un-pinned. Thus, it seemed not unexpected that the surface of planar FET devices was unstable. Nevertheless, a number of investigations published in the literature, claimed surface conditions insensitive to pH-values or sensitive to only few ionic species [21]. It seemed therefore, that it may be possible to in-situ passivate the surface during device processing. Such a treatment was found in connection with the newly developed self-aligned gate fabrication process described below involving an Au-etchback by a KI/I_2 solution.

2. Experimental

The devices were fabricated on nominally undoped homoepitaxial films on single crystals. The homoepitaxial layer had a thickness of 100 nm, and was grown in microwave plasma CVD reactor in a H_2 atmosphere containing 1.5% of CH_4 at 650 °C and pressure of 15 Torr. Subsequently, the layer was treated in hydrogen plasma and cooled down to R.T. in hydrogen atmosphere to obtain the hydrogen terminated diamond surface. Device isolation was obtained by using low energy oxygen plasma. Thus, the conducting active device areas were as-grown hydrogen terminated and the surrounding passive areas were isolating by oxygen termination.

Due to the un-pinned nature of the hydrogen-terminated diamond surface, the barrier height of metal to diamond contacts depends strongly on the metal work function as mentioned above. E-beam evaporated Au has been used for ohmic contacts and Al for Schottky contacts, respectively. The contact fabrication sequence is illustrated in fig. 4. Firstly, the Au-layer covering the entire active area is patterned by etching. Next, a three-layer e-beam lithography process has been used for the definition of the sub-µm gate patterns. The footprint of the gate has then been opened by etching back the Au layer in a KI/I_2 solution and was therefore self-aligned in respect to the Au contacts. Subsequently the gate metal (Al) has been deposited and patterned by lift-off. FETs have been fabricated both on HTHP type Ib substrates and on a diamond quasi-substrate (a single crystal substrate detached from an $Ir/SrTiO_3$ substrate [22]).

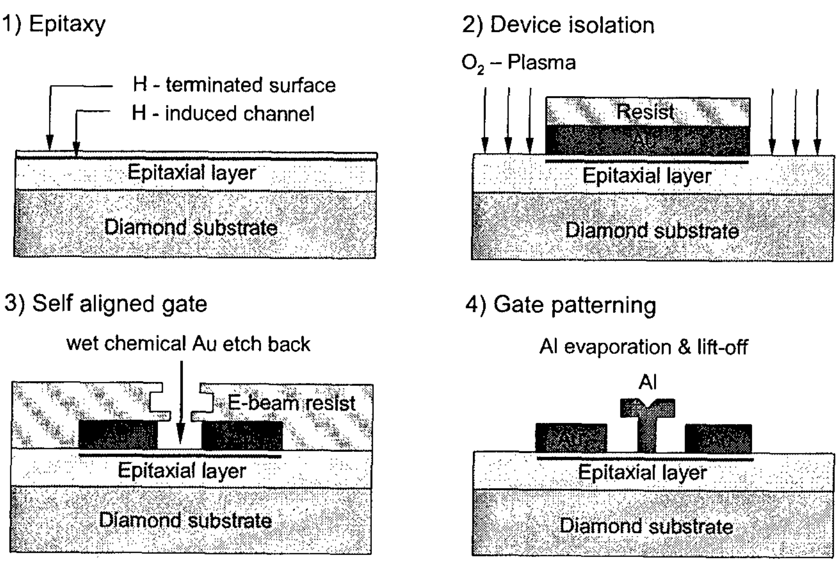

Fig. 4. Processing sequence of self aligned gate of diamond Schottky-gate FET technology.

To test the free surface in the liquid environment, diamond surface channel structures were prepared as described in [20] with contacts and leads entirely isolated and protected by epoxy. After various surface treatments these structures were tested in 0.1 M H_2SO_4 acidic and in 0.1 M KOH basic water solutions.

3. Switching and large signal characteristics

In our previous experiments the hydrogen terminated diamond surface has been treated with resist and developer to pattern the contacts. This was generally followed by a rinse in acetone and isopropanol, avoiding oxidizing agents. The characteristics of this surface may be summarized as shown in the following figs. 5 and 6.

Fig. 5 shows the switching response in atmosphere of an ungated channel between source and drain contacts (source to drain spacing is 5 µm). When switching from the quiescent bias point V_{DS} = 0 V to a drain-source bias of 40 V and 80 V, respectively, the current decreases with time. However, it recovers after switching the bias off, as also shown in fig. 5, where the measured points are obtained by short bias pulsing. The bias pulse must be short enough (~ 1 s) to not disturb the recovery. It seems that the channel becomes slowly depleted by surface charges changing the surface potential or acting as virtual gate. The effect is reversible with bias and thus an electronic surface instability.

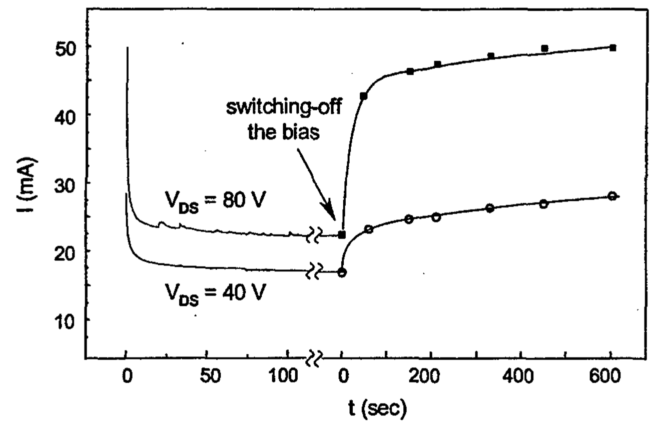

Fig. 5. Previously observed current instability of an ungated channel when switching on the bias between contacts and subsequent current recovery after switching-off the bias (the measured points are obtained after short ~ 1 s bias pulse not disturbing the recovery).

On the other hand, when trying to remeasure the FET output characteristics up to high forward gate bias, the output current is degraded with each trace (see fig. 6) and not recovered. Thus, this effect is not reversible and points towards a permanent degradation of the surface charge state. S-parameter measurements characterizing the high-speed performance, were therefore mostly taken in the lower part of the output characteristics using virgin samples [16].

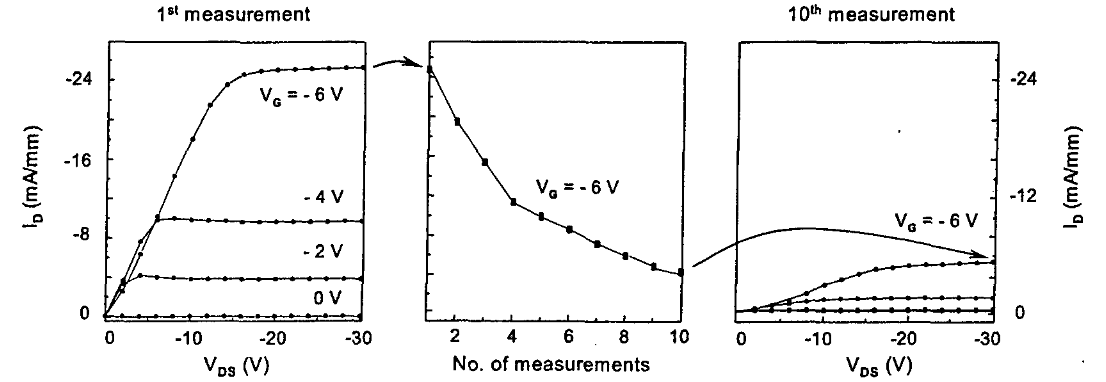

Fig. 6. Previously observed irreversible degradation of MESFET output characteristic after 10 measurements, after Ref. [16].

The characteristics of ungated samples in the liquid environment are shown in fig. 7. Here the sample has been dipped into 0.1 M H_2SO_4 acidic and in 0.1 M KOH basic water solutions with pH values approx. 1 and 11, respectively. The experiment started with pH = 1. After each dip the sample was rinsed in deionized water and then brought into contact with the next solution. The pH sensitivity of the device in the first sequence shows that indeed the surface appears unpinned. The highest current level and thus smallest channel depletion is obtained for pH = 1, the channel being successively depleted with increasing pH. Repeating the sequence reveals that the initial open channel condition cannot be reproduced. In addition, after each sequence a further reduction in open channel current is observed. Thus this effect is not reversible and finally the channel appears depleted at all time. This points towards the build-up of an in-situ passivation layer charging up the surface and depleting the channel. The driving force can be expected to be the highly polar surface. It seems that this passivation layer due to adsorption cannot be removed anymore or may even react with the surface resulting in a change of its termination.

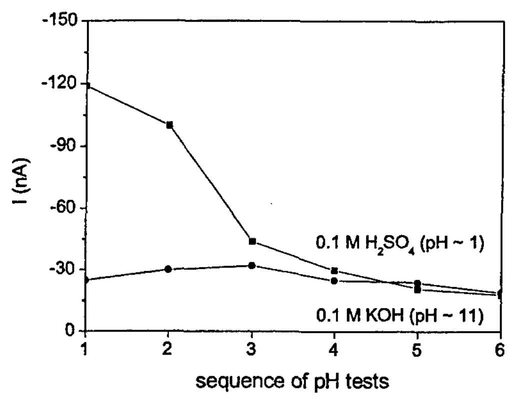

Fig. 7. Degradation of an ungated channel in aqueous solution of different pH values of as-fabricated samples.

In the new experiment the surface was treated with a KI/I_2 Au-etch solution, then rinsed in deionized water and dried before deposition of the Al-gate (in case of the FET) or before immersing into the liquid (in case of the ungated structures). Thus, in the case of the FET the surface treatment was effective to the open surface as well as to the Schottky gate interface.

At first, the response of ungated structures to the liquid environment shall be discussed. The same sequences were performed as described above, in fact on the same device after KI/I_2 treatment. The result is shown in fig. 8. The starting current level is about 5 times higher than before. This means that this time the current more than recovered after the first series of sequences, which showed degradation. This means also that indeed an adsorbed passivation layer had caused the degradation in the first case and not a non-reversible chemical reaction. Furthermore, in the first case the surface conduction (for an open channel) had already been degraded and depleted the channel partially by the previous resist deposition and development routine. Now, even after 6 sequences going through the full cycle of pH-treatments, still 90% of the current level is seen. The surface has been essentially stabilized without loosing its property of being un-pinned. It seems important to identify the chemical mechanisms behind. This is still under investigation and will however need to involve a full electrochemical analysis.

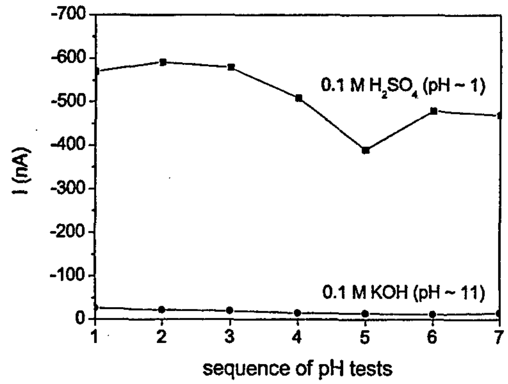

Fig. 8. An ungated channel in aqueous solution of different pH values after KI/I_2 treatment.

In respect to the Schottky-gate FETs, repeatedly large signal measurements were performed using a parameter tester and a power bench at 1 GHz. In fig. 9 is shown the IV-output characteristics of a virgin device with 0.8 μm gatelength. Stressing the device for 10 minutes in the open channel condition (V_{GS} = - 3.5 V and V_{DS} = - 20 V) shows an increase of the maximum current by approx. 20% (see fig. 10). This is mainly related to a stabilization of the Schottky barrier characteristics, resulting in a decrease of (forward) pinch-off voltage of this enhancement mode device. No external current limiter is visible stemming from the open channel areas between the contacts. Power measurements in class A were first performed with a 50 Ω load scanning the drain bias up to - 40 V. The level of power saturation could be obtained for each scan and thus the maximum peak in RF-current. Adding up the different scans will then result in an RF current envelope of the output characteristics. As expected, it surpasses the DC output current levels obtained from the curve tracer measurement. Thus no

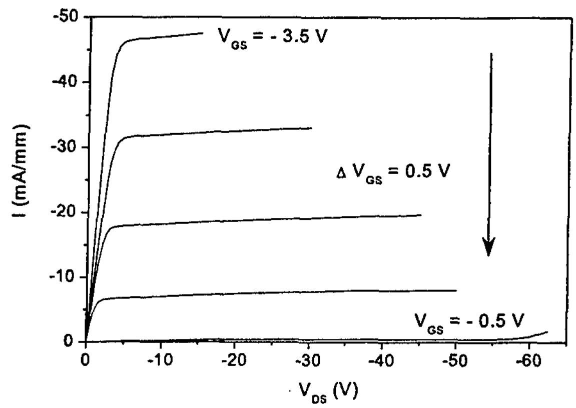

Fig. 9. I-V output characteristic of surface channel FET with 0.8 μm gate length. This graph is constructed of 2 measurements. The breakdown curve is added.

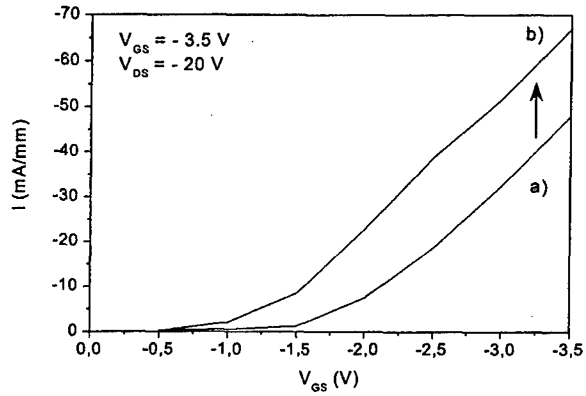

Fig. 10. Transfer characteristics
a) measured on a virgin device b) after bias stress at V_{GS} = - 3.5 V and V_{DS} = - 20 V for 10 min.

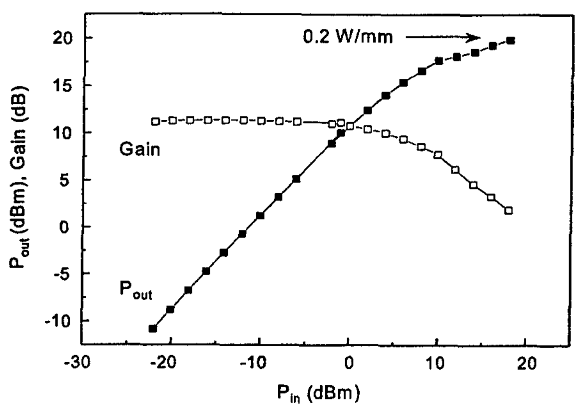

Fig. 11. Large-signal measurements at 1GHz for class-A bias point V_{DS} = - 40 V, V_{GS} = - 2.2 V, after Ref. [23].

current clipping or RF current degradation is observed. Using the optimum available load on the tuner system (approx. 400 Ω) has then resulted in the first diamond FET power measurement of 0.2 W/mm at V_{DS} = - 40 V (see fig. 11) with an associated linear gain of 12 dB as recently reported at the 60^{th} DRC [23].

4. Conclusions

Although the diamond crystal does not contain a spontaneous polarization, the surface becomes highly polar upon termination. After growth in a hydrogen rich environment, this is the H-termination with a highly positively charged surface. This surface is un-pinned, indicating a high bondstrength of this atomic surface layer and no (noticeable) surface states within the bandgap. This is very similar to other polar materials like hexagonal GaN. Therefore, it is not surprising that surface adsorbates can charge the surface, resulting in effects similar to the virtual gate effect in GaN based FET structures. Thus, the H-terminated diamond surface will behave electronically highly unstable, which will in turn affect the stability of FET channel sheet charge densities. In the case of diamond the surface conditions can change and deteriorate irreversibly, causing permanent current degradation. Thus, in-situ passivation by adsorbates plays an important role.

These instability and degradation phenomena have been severe enough to prevent large signal operation. However our recent results indicate, that the instability and degradation mechanisms can be influenced by specific surface treatments. The present understanding is, that the surface dipole layer is stabilized by an in-situ passivation of specific ionic adsorbates. However, this picture is still highly speculative. Nevertheless the stabilization of the FET large signal characteristics have by now been observed in devices fabricated with various gatelengths and on various substrates, namely a diamond quasi-substrate and also on HTHP synthetic crystals with homoepitaxial active layers.

Eventually it is hoped that a refined surface treatment may allow to further improve of the power handling capability of diamond surface channel FETs, which is still approx. 2 orders of magnitude below expectations [24].

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