An overview on recent developments in RF and microwave power H-terminated diamond MESFET technology

An overview on recent developments in RF and microwave power H-terminated diamond MESFET technology

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Abstract — Thanks to its wide bandgap, exceptionally high thermal conductivity and relatively high carrier velocities, diamond exhibits attractive semiconductor properties that make it an interesting candidate for high power, high frequency and high temperature solid-state microelectronic devices, able to withstand harsh environmental conditions (in terms of temperature and/or radiation). The development of a diamond transistor technology has been restricted for many years due to the difficulty in implementing conventional acceptor or donor bulk doping strategies with satisfactory activation at room temperature. More recently, a breakthrough in diamond MESFET technology was represented by the introduction of surface diamond *p*-doping by means of H-termination, opening the way to interesting development in the microwave field.

The paper presents an overview on recent developments in H-terminated diamond MESFETs for power RF and microwave applications. After an introduction to the diamond technology and device state-of-the-art performance, the physics-based and large-signal modeling of diamond MESFETs is discussed.

Index Terms — Diamond, MESFETs, power amplifiers.

I. Introduction

Diamond as a semiconductor exhibits several attractive properties that make it a promising candidate for the fabrication of high power, high frequency and high temperature solid-state microelectronic devices, especially for use under adverse conditions and in harsh environments [1]-[2].

Table I shows a summary of the main semiconductor properties of diamond in comparison with Si, GaAs, SiC and GaN. High-temperature and high-power operation follows from the wide bandgap, high breakdown field and high thermal conductivity (5 times than of Cu). High-frequency performance is also possible, thanks to the relatively high intrinsic carrier mobility (4500 cm^2/Vs for electrons and 3800 cm^2/Vs for holes) [3] and very high saturation velocity (1.5×10^7 cm/s for electrons and 1.1×10^7 cm/s for holes) [4]. Finally, the low dielectric constant may reduce the capacitive loading and allow for larger area devices to be fabricated for a specified impedance so that larger RF currents and higher RF power may be achieved [5].

Electronic and optoelectronic devices based in diamond have been investigated during the two last decades and have demonstrated impressive performance despite the immaturity of diamond technology when compared to other widegap semiconductor technologies like SiC or GaN.

TABLE I
Main electronic properties of diamond vs. other conventional or wide bandgap semiconductors

Property	*Si*	*GaAs*	*6H-SiC*	*GaN*	*Diamond*
E_G, eV	1.12	1.43	3.03	3.45	5.45
ε_r	11.9	13.1	9.66	9	5.5
E_{br}, kV/cm	300	400	2500	2000	10000
μ_e, $cm^2/V/s$	1500	8500	500	1250	4500
μ_h, $cm^2/V/s$	600	400	101	850	3800
κ,W/cm/K	1.5	0.46	4.9	1.3	22

In fact, the development of diamond-based electronic devices has been hindered for many years by the difficulty in achieving efficient diamond doping, in particular n-type, due to the high activation energies of dopants in diamond. More recently, the investigation turned towards unipolar devices based on metal/semiconductor junctions exploiting a new paradigm for surface doping, i.e. H-terminated diamond [6]-[8]. Diamond MESFETs based on this principle have been investigated, with interesting microwave properties.

II. Diamond MESFET technology & RF performances

The starting material for diamond device development is a synthetic substrate produced through the High-Pressure High-Temperature (HPHT) process leading to single crystals some millimeters in dimension with a good crystallographic structure but typically with high impurity levels. Layers grown by Chemical Vapor Deposition (CVD or MPECVD) provide a higher quality diamond substrate for the development of active devices. The CVD film can be single-crystal when grown on a diamond substrate or polycrystalline with varying grain size depending upon the host (often non-diamond) substrate. The electronic properties of polycrystalline large-grain films approach that for single-crystal diamond, see [9]. Since intrinsic diamond is an insulator, a method for introducing sufficient quantities of free charge is required to produce electronic devices. Both nitrogen and phosphorus have been used with some success for n-type doping and boron for p-type doping [10]. For n-type diamond, P has proven to be the preferred dopant due to a lower electron activation energy of ~

0.6 eV [11] compared to ~ 1.6 eV for N [12]. Due to the lower activation energy of B (~ 0.37 eV), and the associated “hopping” transport mechanism, greater success has been achieved in the production of p-type diamond films; however, the hole mobility is found to degrade severely in boron doped diamond despite attempts to introduce delta-doped structures [13].

A breakthrough in the development of diamond-based field effect transistors was the identification of a p-type surface conductive channel found on the highly polar H-terminated diamond surface (while the O-terminated surface is insulating). Experiments show that an adsorbed layer from the atmosphere on the H-diamond surface induces this surface conductivity [14] by receiving electrons from the diamond valence band, giving rise to a two-dimensional hole gas (2DHG) within the diamond. This process is shown in Fig. 1. The p-type 2DHG (located less than 10 nm below the diamond surface) typically exhibits hole sheet densities between 10^{10} and 10^{14} cm^{-2}, and Hall mobilities between 1 cm^2/Vs and 100 cm^2/Vs [15]. The reliance upon the naturally adsorbed atmospheric surface layer for doping has thus far limited the robustness and stability of operation of these devices [16]. Various techniques have been attempted to control and stabilize the 2DHG by replacing this adsorbate layer with more stable agents. These have met with mixed success, where often the hole density within the 2DHG is reduced or the encapsulation material is little more robust than the adsorbed atmospheric layer [17]-[18]. Promising results have recently been reported however through exposure of the H-diamond surface to NO_2 [19], or utilizing high electron affinity materials such as MoO_3 [20] to not only improve stability, but also increase the 2DHG carrier concentration substantially.

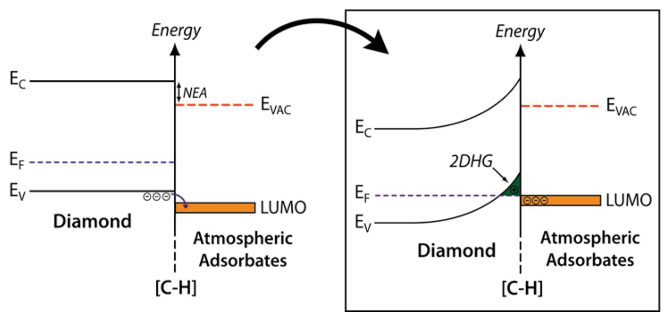

Fig. 1 The surface transfer doping process in H-terminated diamond exposed to atmosphere

Concerning the DC and RF performance of H-terminated single-crystal diamond MESFETs, drain current densities of the order of 350 mA/mm have been demonstrated by different research groups with high g_m values up to 150 mS/mm [29],[30]. Even higher performance has been reported in [21] with a maximum drain current density of 1 A/mm and a g_m of 520 mS/mm. For diamond FETs realized on single crystal diamond, the highest reported cut off frequency is 53 GHz [22] for a device with a gate length of 50 nm, and the highest value of f_{MAX} reported is 81 GHz for a device with a gate length of 200 nm [23]. The highest measured output power density at 1 GHz is 1.26 W/mm with 400 nm gate length and 1 mm periphery [6]. A still higher operating output power density, up to 2.1 W/mm with 100 nm gate length MESFET transistor, has been demonstrated with 10 dB gain [24]. Similar performance was obtained from polycrystalline MESFETs (grain size ~ 100 µm) [25], with a maximum I_D density of 550 mA/mm, a g_m of 150 mS/mm and f_T and f_{MAX} values of 45 and 120 GHz, respectively, among the highest reported for diamond [26]. A larger current density (790 mA/mm) is reported in MISFETs [41]. The reported maximum power density is however lower. In [27], power performance has been evaluated experimentally on a 2×50 µm 200 nm gate length MESFETs operating in class A; the measured output power density at 2 GHz is 0.2 W/mm at -14 V drain-source voltage bias.

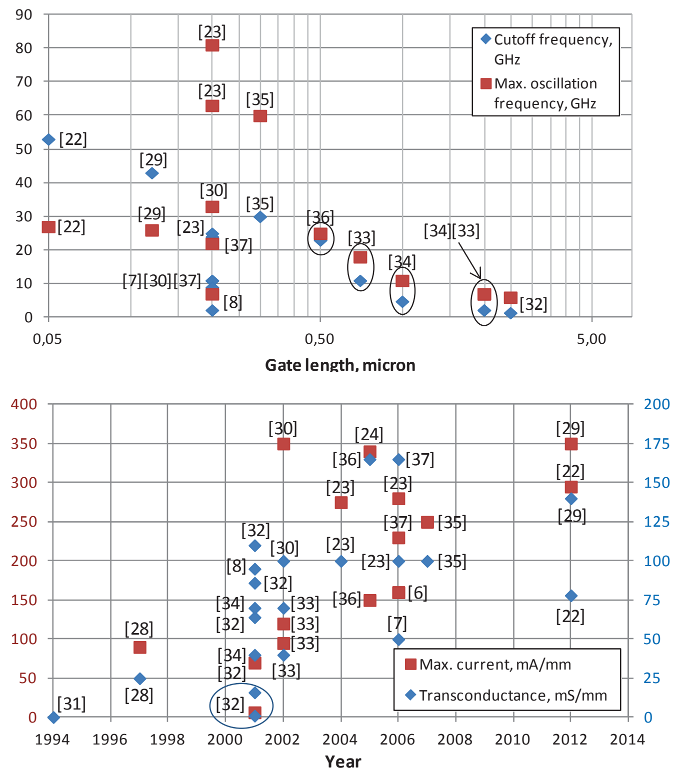

Fig. 2 Charts summarizing the published performance of single-crystal H-terminated diamond MESFETs and MISFETs. Above: f_T and f_{MAX} *vs.* L_g; below: evolution of $I_{DS,max}$ (left-hand axis) and g_m (right-hand axis) normalized with respect to the gate periphery from 1994 to 2013.

A synthesis of the performance evolution of single-crystal H-terminated diamond devices is shown in the charts of Fig. 2 and Fig. 4. Fig. 2 (above) reports the f_T and f_{MAX} of a number of literature devices (the reference is close to each marker) shown as a function of the gate length. The minimum gate length achieved so far is 50 nm. From the chart in Fig. 2 (above) we clearly see the well-known increasing trend when decreasing the gate length; however, below 200 nm there is significant space for improvement, as shown by the poor performances of such short-gate devices in terms of the f_{MAX}. Extrapolating the results above 200 nm to shorter gate length with optimized technology we see that f_{MAX} in excess of 100 GHz are within reach for gate lengths below 50 nm. Fig. 2 (below) shows on the other hand the historical evolution of the normalized maximum drain current and transconductance, where a clear increasing trend can be detected.

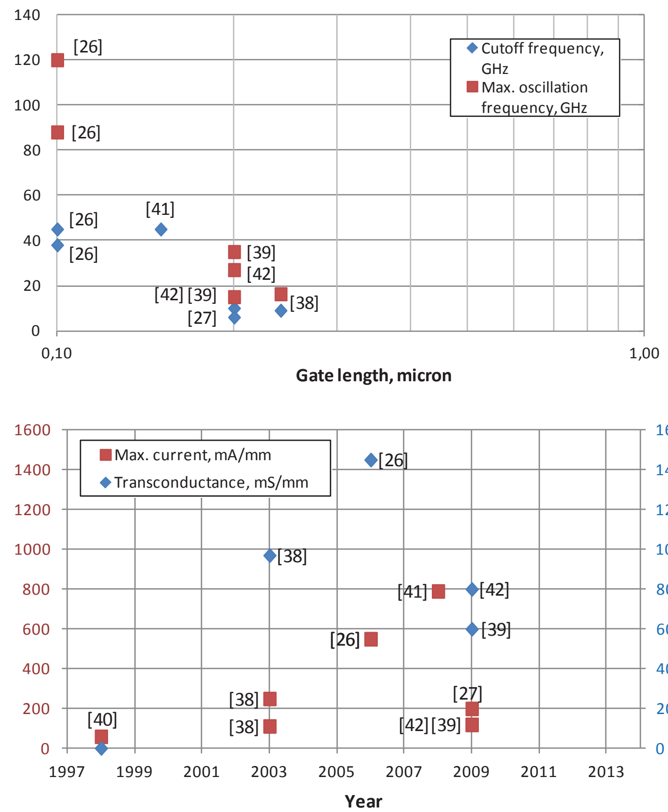

Fig. 3 Charts summarizing the published performance of polycrystalline H-terminated diamond MESFETs and MISFETs. Above: f_T and f_{MAX} *vs.* L_g; below: evolution of $I_{DS,max}$ (left-hand axis) and g_m (right-hand axis) normalized with respect to the gate periphery in years 1997-2011.

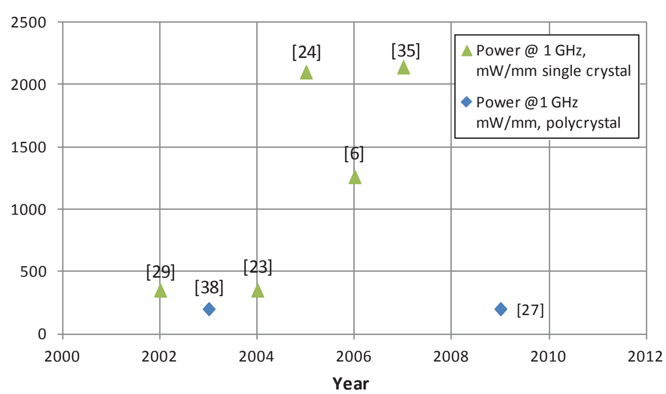

Fig. 4 Summary chart of demonstrated RF output power normalized to the gate periphery at 1 GHz for single-crystal and polycrystalline diamond MESFETs and MISFETs. The marker from [27] is measured at 2 GHz.

A similar trend can be observed in Fig. 4, concerning the evolution of the power density, still, however, far below the theoretical expected value. Fig. 3 (above and below) reports similar data concerning devices realized on a polycrystalline diamond substrate, with similar trends. Indeed, when compared to single-crystal ones, polycrystalline devices exhibit interesting properties in terms of operating frequency, DC performance and output power (see Fig. 4); of course, the available defect-free semiconductor area is an issue in such devices.

Note that some of the devices presented in the previous charts ([24],[27],[32]-[39],[41]-[42]) are indeed MISFETs rather than MESFETs, due to the presence on an intentional insulating layer between the gate electrode and diamond surface.

III. Diamond MESFET modelling

Despite the promising RF and power performance that has already been demonstrated, the modelling of H-terminated diamond MESFETs has been rarely addressed, both from a physics-based and from a circuit-oriented standpoint. From the physics-based point of view, a few drift-diffusion examples [43]-[45] have been reported, wherein the channel is modelled by an empirical bulk acceptor dopant profile, thus leaving in the background a physical description of the 2DHG formation and control by the applied bias. In fact, although the surface-transfer doping model is now generally accepted to accurately describe formation of the 2DHG within the atmosphere-exposed FET access regions, the detailed mechanism for the 2DHG charge control beneath the Schottky gate contact (typically Al) is still an object of investigation. On the other hand, measured DC and small-signal device parameters highlight marked similarities with the wide class of compound semiconductor HEMTs; such an analogy can be exploited to set up a possible physics-based framework aimed at developing interpretation guidelines for further experimental studies and investigating physical causes of degradation such as surface states and defects.

To briefly address the above mentioned similarity (as well as open issues in the direction of developing a reliable physics-based model), we can consider the following experimental evidence: i) the observed limited gate leakage up to high forward bias that conflicts with the hypothesis of a 2DHG directly located at the diamond surface, as implied by the surface-transfer doping model; ii) the typical bell-shaped transconductance (g_m) as a function of V_{GS} (see Fig. 5), observed in both single-crystal [46] and polycrystalline FETs [27], [47], well before the onset of gate breakdown. Such behavior could be correlated to a number of physical causes, or their combination, among which we can highlight

- saturation of channel hole density at high gate voltage, possibly induced by the onset of free hole conduction in a region with degraded transport properties;
- nonlinear behavior of the parasitic source and drain resistances [48], related to specific carrier injection

mechanisms, possible velocity saturation as well as geometrical effects;

- effective channel mobility degradation at high normal electric fields, similarly to the mobility degradation found in MOSFET inversion layer [45].

The assessment of such mechanisms and their effective impact on the device performance shall be pursued through further experimental studies both on FET structures as well as Schottky contacts, supported by physics-based modeling. Regardless of the detailed mechanism underlying the observed g_m compression, measured DC and AC parameters seem compatible with a Schottky barrier bandstructure as shown in Fig. 6. In this heterostructure-like picture, the charge channel formation is induced by surface dipoles and/or transfer doping from a δ-distributed acceptor level located, close to the diamond surface, in a 4-5 nm thick interfacial layer (IL) separating the diamond surface from the Al gate.

Besides being able to reproduce typical I-V and C-V characteristics of rectifying H-diamond/Al contacts, such a hypothesis finds support in microstructural characterizations [49] where Transmission Electron Microscope (TEM) images of the Al-diamond contact demonstrate the presence of an interface layer that is a few nanometers thick with morphology different from that of Al and diamond,. Based on the devised heterostructure-like analogy, quasi-2D MESFET models have been developed following well known approaches already developed for HEMTs. Very good preliminary results, not reported here, indeed show that that such charge control model may provide physical support to the use of specific equivalent circuit large-signal models, such as the Chalmers (Angelov) model [50].

Circuit-oriented modelling of diamond MESFETs has been mainly confined to small-signal equivalent circuit extraction [47],[51] based on scattering parameter measurements up to 40 GHz. A large-signal nonlinear circuit-oriented model for surface channel H-terminated diamond MESFETs has been recently proposed by the Politecnico di Torino research group [52], based on the Chalmers model approach [50]. The model, implemented within the ADS Agilent CAD tool, is extracted from DC and multi-bias small-signal characterization, and then validated against RF power characterization [27]. The approximation provided by the Chalmers model is able to accurately model the DC curves (see Fig. 7) but also the S-parameters (Fig. 8). Results concerning the behavior of the Chalmers model applied to diamond devices over a wide range of RF input power, in terms of output power, gain, and power added efficiency are reported in Fig. 9. The encouraging results shown were found not only concerning the devices considered initially [27], but also other devices from the literature[24]. By means of the outlined large-signal modelling approach, simple microwave power amplifiers can be designed. From a technological standpoint, improvements are currently sought, as mentioned in Sec. II, to the device long-term stability, that is essential for practical applications.

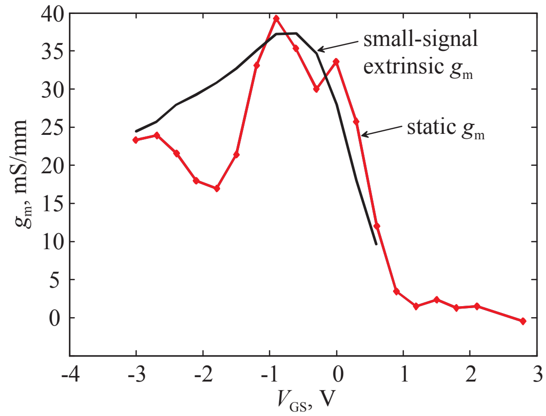

Fig. 5 DC and small-signal transconductance (g_m) of a MESFET on poly diamond (L_g=0.2 µm) [52].

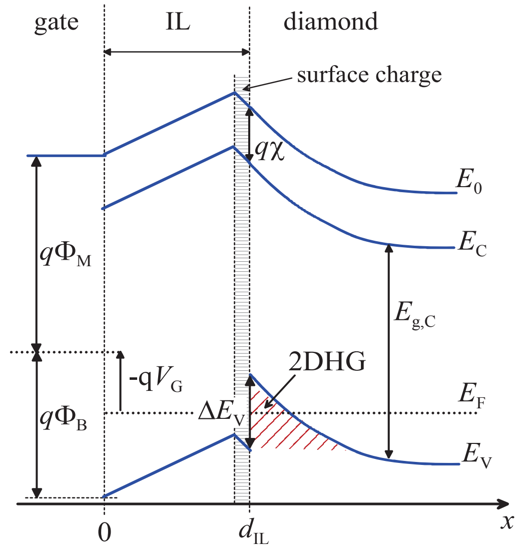

Fig. 6. Qualitative sketch of the postulated energy band diagram for the gate-IL-diamond heterostructure.

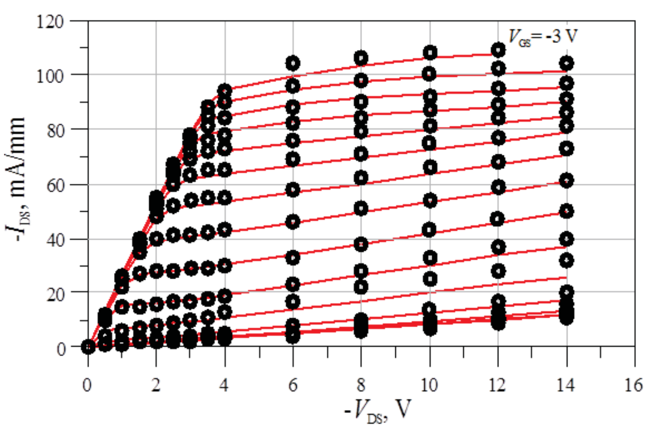

Fig. 7. Simulated (lines) and measured (symbols) DC characteristics of a MESFET on poly diamond (L_g=0.2 µm) [52].

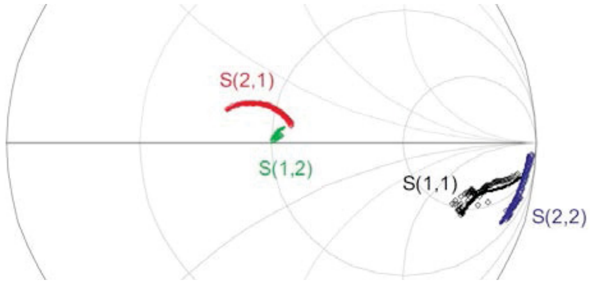

Fig. 8. S-parameters at the bias point V_{DS} = -14 V, V_{GS} = -0.9 V: measurements (symbols) and model (solid lines) [52].

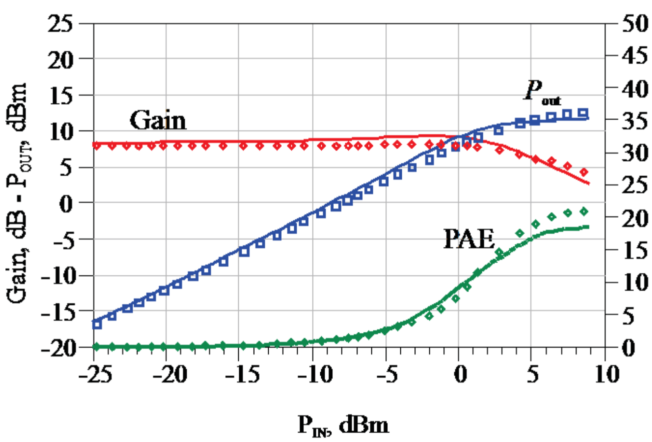

Fig. 9. 2 GHz P_{in}-P_{out} on the PAE optimum Z_L. Measured (symbols) and simulated (lines) gain, P_{out}/1 mm gate periphery and PAE for V_{GS} = -1 V, V_{DS} = -14 V [52].

IV. Conclusion

We have presented an overview on recent developments in H-terminated diamond FET technology for RF and microwave power applications. Despite the relative immaturity of the technology and the remaining unsolved issues in terms of process stability and device passivation, the promising results obtained highlight H-terminated diamond MESFET technology as a possible competitor in the field of widegap semiconductor, high-frequency power transistors. A short discussion has been presented on physics-based and circuit-oriented diamond MESFET modelling approaches, demonstrating that modelling paradigms derived from III-V and III-N analysis can be successfully applied to diamond-based devices.

Acknowledgement

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