# Large-Signal RF and DC Performance of p-Type Diamond FETs

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**Abstract**

**Large signal RF and DC simulation of diamond FETs using incomplete dopant ionization statistics is reported for the first time. The simulation was performed using a harmonic balance circuit simulator which uses the two-dimensional simulator, PISCES-IIB, to investigate the high temperature performance of FET devices. Simulations indicate the DC and RF performance of diamond MESFET is improved as temperature is increased in a temperature range of 573 K to 923 K. At 923 K the simulated diamond MESFET produces about 0.5 W/mm for an operating frequency of 3 GHz and 29% power-added efficiency (PAE) at 19 dBm input power. Due to the high activation energy of dopant in diamond the DC and RF performance of device is found out to be dominated by the carrier ionization process.**

## 1. Introduction

The properties of semiconducting diamond make it an excellent material for high-frequency, high-power and high-temperature device operation.This is due to diamond's high saturation velocity, wide band-gap and high thermal conductivity [1]. Despite the excellent properties, however, a present disadvantage of diamond is the low ionization probability of carriers due to high activation energies. For this reason, the use of an incomplete dopant ionization model in simulation is important for determining the high temperature performance of diamond devices. For verification, the simulated DC performance of diamond IGFET is presented and compared with experimental results. Several physical models including the incomplete ionization model are employed in diamond device simulation. The temperature dependence of diamond MESFET DC and RF performance is investigated in the temperature range of 573 K to 923 K.

## 2. Simulation Experiment

The RF simulations are performed by a harmonic balance circuit simulator [2] which utilizes the accuracy of the two-dimensional numerical device simulator, PISCES-IIB, to simulate MESFETs of various geometries and materials [3]. The harmonic balance simulator extracts the FET gate and drain current and capacitance characteristics

| MATERIAL PARAMETERS | VALUE |
|---|---|
| Activation energy of Dopant (eV) | 0.34 |
| Low field mobility ($cm^2V^{-1}s^{-1}$) | 30 |
| Energy gap (eV) | 5.45 |
| Permittivity | 5.7 |
| Saturation velocity of holes ($cm/s$) | $2 \times 10^7$ |
| Valence band density of states (300 K) | $1.8 \times 10^{19}$ |
| Life time of holes ($s$) | $1 \times 10^{-9}$ |

Table 1: Material parameters used in the simulation.

and then performs large and small signal analysis. Several physical models are employed in the simulations. For example, the mobility of the carriers depends on both the electric field and temperature, and the carrier velocity saturates at high fields. The effect of temperature on free carrier activation is modeled using Fermi-Dirac statistics for incomplete ionization. Several parameters such as intrinsic carrier concentration, density of states, and band gap energy exhibit temperature dependence and are included in the simulation. The harmonic balance simulator utilizes a table based look-up approach (which describes the device) to increase the overall efficiency of the simulator when performing DC and RF simulations as well as optimizations and yield analysis. The semiconductor devices in this work are characterized using PISCES-IIB. DC-IV and contact capacitances are extracted and formed into a two-dimensional look-up table which spans the typical drain and gate operational voltage range. The look-up table is then automatically incorporated into the harmonic balance simulator. The harmonic balance simulator has demonstrated excellent accuracy in predicting the RF performance of a variety of industrial devices fabricated from GaAs [2].

## 3. DC simulation of diamond IGFET

For verification, the DC simulation of diamond IGFET is performed using the device structure fabricated by Hewett et. al. [4]. The IGFET was fabricated in a concentric ring structure. The diameter of the circular gate was accounted for to properly compare the measured and the simulated drain current. The channel depth and channel doping concentration are 0.18 $\mu$m and $1.1 \times 10^{17}$cm$^{-3}$, respectively. The oxide thickness on top of the channel is 0.1 $\mu$m and the workfunction of the gate electrode is 5.1eV. The material parameters used in the simulation are listed in Table I. Figure 1(a) demonstrates an excellent match between the simulated and measured IGFET DC characteristics. Incomplete ionization of acceptor doping was found to severely limit the peak channel current of the device at room temperature. The peak drain current(at 0 gate bias, and 50$V_{ds}$) is only 45 $\mu$A. The input capacitance is found to be approximately 0.3 pF. The gate displacement current was calculated to be approximately 40 mA. Thus, at RF frequencies, the gate displacement current dominates the device channel current by three orders of magnitude and the resulting theoretical RF power performance is very poor.

## 4. Analysis of diamond MESFET at high temperatures

The material parameters used for the analysis of the diamond MESFET are extracted from the DC simulation of the diamond IGFET previously discussed. The same material parameters are also found to accurately characterize polycrystalline IGFETs [5] with the exception of dopant activation energy. The structure of the simulated diamond MESFET is shown in Figure 1(b). The structure of the MESFET has been designed to be appropriate for device performance at high frequencies. The operation temperatures are 573 K, 773 K, and 923 K, and the resulting mobilities are calculated to be 600, 100, and 83 $cm^2/V-s$, respectively. Figures 2(a)-(c) show the simulated MESFET I-V curves. The drain current at 773 K is slightly higher than that at 573 K due to the increased carrier activation. The gate width is 1 mm and gate voltages vary from 0 to 20 V. The drain current at 923 K shows approximately a 20% increase compared to that at 773 K because of a higher activated carrier concentration, with similar mobilities at both temperatures. At higher temperature, there is an improvement in RF output power as well as gain and power-added efficiency (PAE) as shown in Figures 2(d)-(f). The result of RF simulations clearly show a consistent increase in RF performance with the increase in channel current as the temperature increases. The device was characterized at an operating frequency of 3 GHz with $V_{gs}$ = 7V and at $V_{ds}$ = 30V . The MESFET device produced approximately 0.5 W/mm of RF output power at 923 K. The PAE at this temperature has approximately 29% peak at an input power of 19 dBm. The linear gains are about 12.0, 13.5, and 15.0dB at 573 K, 773 K, and 923 K, respectively. The comparison of the DC and RF performance at different temperatures shows a distinct trade-off between decreased mobility and carrier saturation velocity and the increased activated carrier concentration with increasing temperature. Due to a high value of activation energy for ionization of acceptors (Boron) in diamond, the magnitude of channel current and thus the RF performance are shown to be dominated by the ionization process.

## 5. Conclusion

This study shows that the DC performance of diamond IGFET can be predicted by employing proper material parameters. The comparison of the DC and RF performance of diamond MESFET at different temperatures indicates a trade-off between decreased mobility and carrier saturation velocity and increased activated carrier concentration with increasing temperature. It is shown that the theoretical RF performance of diamond MESFETs improves with increasing temperature. This is due to a high value of activation energy of dopant ionization.

## References

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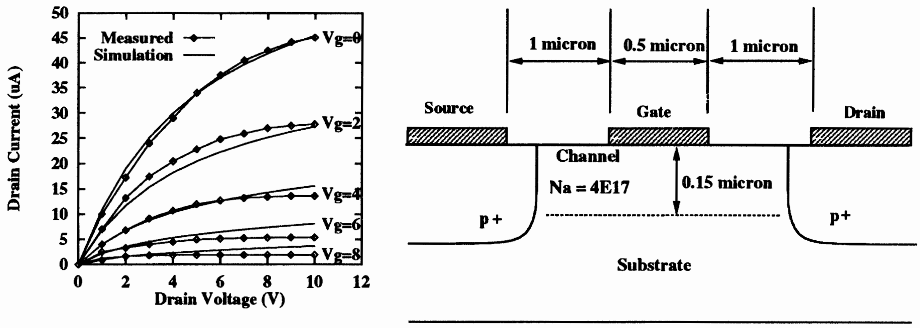


(a) (b)

Figure 1: (a)Comparison between the measured [4] and theoretical I-V characteristics for a diamond IGFET. (b)Cross sectional sketch of the diamond MESFET.

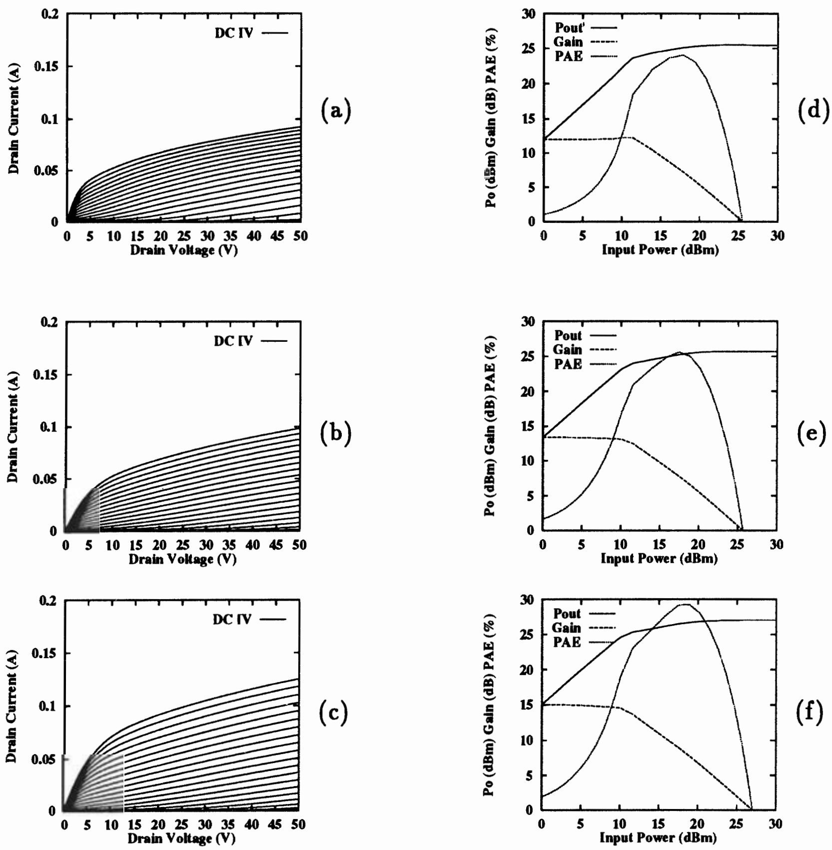


Figure 2: Simulated I-V characteristics for a diamond MESFET at (a) 573 K, (b) 773 K, and (c) 923 K. The gate voltage ranges from 0 to 20V in steps of 2V. Simulated RF (3 GHz) characteristics for a diamond MESFET at (d) 573 K, (e) 773 K, and (f) 923 K.