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Temperature Dependence of Diamond MOSFET Transport Properties

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Abstract

Semiconducting diamond is one the most attractive ultra-wide bandgap materials for power-electronics applications because of its outstanding electrical and thermal properties. Nowadays, the recent advanced in diamond growth and oxide/diamond interfaces engineering have allowed the achievement of inversion channel diamond mosfet. This breakthrough opens the way to the fabrication diamond power mosfet and even the insulated gate diamond bipolar transistors. However, to guarantee the high performance of diamond power mosfet, much remains to be understood such as the effect of a thermal stress on diamond mosfet electrical features. In this work, the transport properties of p-channel diamond mosfet have been investigated for a temperature ranging from 6.5 K to 673 K. It has been found that the high temperature thermal cycling improved the drain current by 166 %, channel carrier mobility by 77%, and allows a minimization of devices threshold voltage. On the other hand, the diamond mosfet can operate at very low temperature such as 6.5 K, thus demonstrating the formation of an inversion channel even at low temperatures. This unexpected inversion channel formation at low temperatures is ascribed to the coupling of hopping transport in impurity's energy band (source and drain) and band conduction in channel's valence band. Indeed, the hopping transport at impurity's energy band counterbalances the effects of high impurities ionization in diamond and constitutes the main transport mechanism at low temperature in heavily doped diamond layers (source and drain layers).

1. Introduction

Owing to its outstanding electrical and thermal properties, diamond is one of the most attractive ultra-wide bandgap semiconductors for power-electronics applications. Indeed, the power switch metrics such as the Baliga's figure of merit (BFOM), Jonshon's FOM (JFOM), Huang's material FOM (HMFOM), and Huang's chip area manufacturing FOM (HCAFOM) [1-3] shows the highest values for the diamond material [1-3]. Over the few last decades, the advanced in diamond growth and doping have allowed the extension of existing basic devices technologies to diamond (Schottky diode, pin diode, field effect transistors FETs). Nowadays, the recent advanced in diamond growth and oxide/diamond interfaces engineering have allowed the achievement of inversion channel diamond mosfet [4]. This breakthrough opens the way to the fabrication diamond power mosfet and even the insulated gate diamond bipolar transistors. However, to achieve high performance diamond power devices that can outperform the existing and emerging technologies, much remains to be understood in many areas such as the diamond mosfet devices physics and design.

In this work, we focused on the temperature dependence of transport properties of basic diamond mosfet. the electrical characteristics of diamond mosfet have been measured in a wide temperature range from 6 K to 673 K. The devices parameters such the channel mobility and the density of interface states and their temperature dependence will be introduced and discussed. On the other hand, the effect of thermal stress on the electrical properties of diamond mosfet will be introduced.

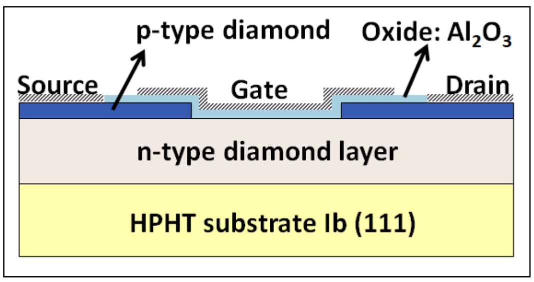

Fig. 1: Schematic of p-channel diamond mosfet.

2. contents

Basic diamond mosfet: the schematic diagram of basic diamond mosfet is shown on Figure 1. The fabricated mosfet is a p-channel mosfet and the detailed fabrication process are reported in reference [4]. A 10 µm thick slightly phosphorus doped diamond layer (n-type diamond layer) was first grown on an insulating diamond substrate (doping density of n-type diamond layer ~ 10^{16} cm^{-3}). A 0.3 µm thick heavily boron doped diamond layers (p-type diamond) was then deposited by selective growth method to fabricate the source and drain layers (doping density of p-type diamond layer ~ 10^{20} cm^{-3}). (Ti/Au) metallic stack was deposited on the source and drain layers and annealed at 673 K to achieve ohmic contacts. A 50 nm thick Al_2O_3 gate oxide then deposited by atomic layer deposition method (ALD). Thus, (Pt/Au) stack was deposited to fabricate the gate electrode.

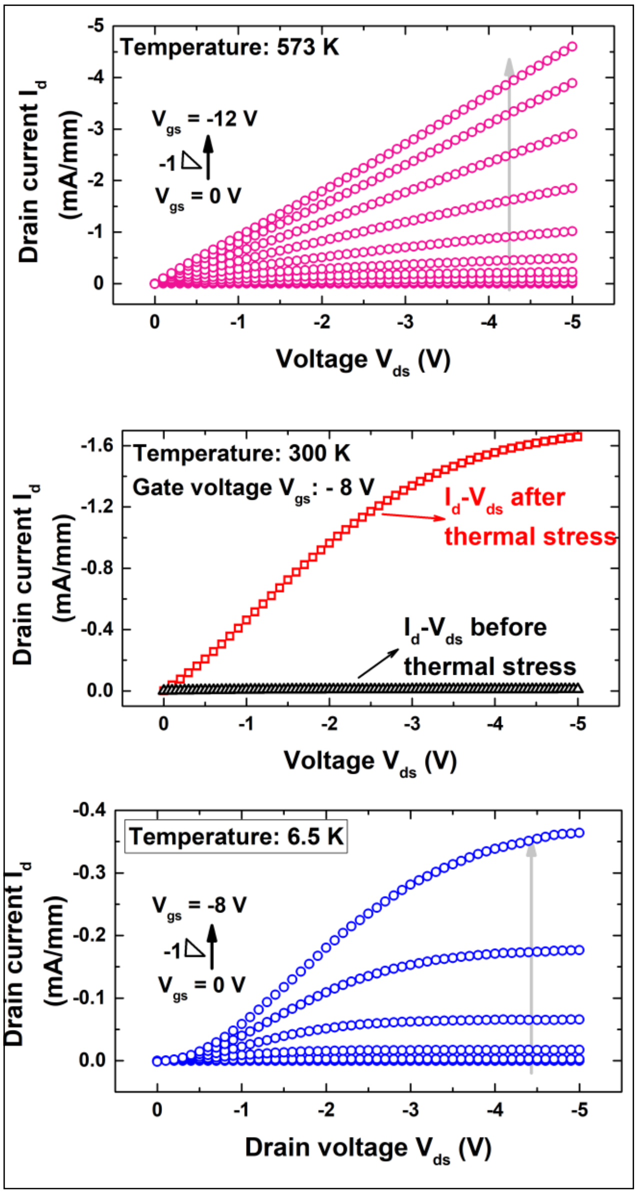

Fig. 2: a) I_d-V_{ds} characteristics of diamond mosfet at 573 K; b) Effect of thermal stress on diamond mosfet characteristics; c) Low temperature (6.5 K) I_d-V_{ds} characteristics of diamond mosfet.

High temperature operation: the electrical characteristics of diamond mosfet have been investigated for temperature ranging from 300 K to 673 K. Fig. 2 a) shows the typical Id-V_{ds} characteristics at 573 K, Id denoting the drain current and V_{ds} the voltage drop from drain to source. Diamond mosfet exhibited good features up to 623 K. Above 623 K, a degradation of mosfet electrical features was observed due to both thermal and bias stresses. On the other hand, it has been observed that the room temperature electrical characteristics of diamond mosfet are improved by the thermal stress. On Figure 2 b), the I_d-V_{ds} characteristics measured before and after the high temperature thermal cycling are shown. Owing to the thermal cycling performed, a RT drain current (V_{ds} of -5 V and V_{gs} of -8 V) of about 1.66 mA/mm was achieved instead of 0.01 mA/mm, thus corresponding to an increase of 166 %. The increase of the drain current can be ascribed to an enhancement of the electrical transport at the oxide (Al_2O_3)/diamond interface and/or to a decrease of the mosfet threshold voltage (Vth). Thus, Vth and the carrier mobility in the channel area have been estimated by using the transfer conductance I_d-V_{gs} characteristics. It has been found that the maximum channel mobility increased from 0.77 cm^2/Vs to 5.9 cm^2/Vs, and the absolute value of Vth decreased from 7 V to 3.15 V.

Low temperature operation: Figure 2 c) shows the I_d-V_{ds} characteristics at 6.5 K. A typical mosfet I_d-V_{ds} characteristics was measured even at low temperature, thus demonstrating the formation of an inversion hole channel. At low temperature, the formation of inversion channel was ascribed to the coupling of hopping transport in impurity's energy band (source and drain layers) and the channel valence band. Indeed, the low temperature electrical transport in diamond is limited by the deep impurity's levels in diamond (0.58 eV and 0.38 eV for Phosphorus donor and Boron acceptor, respectively) leading to a very low density of free carrier. For heavily diamond doped layers like the source and drain layers (see Fig. 1), the effects of deep impurities levels are counterbalanced by the hopping conduction in impurity's energy band, and low resistive diamond layers can be achieved [5]. Moreover, at low temperature, the hopping transport is the main transport mechanism in heavily doped diamond [5]. Therefore, for diamond mosfet operating at low temperature, charge carrier (hole) are assumed to be mainly injected from the impurity's energy band into the channel valence band, thus leading to the formation of an inversion channel.

References

[1] B. Baliga, IEEE-EDL **10** (1989) 455.
[2] A. Huang, IEEE-EDL **25** (2004) 298.
[3] G. Jessen *et al.*, 75th Annual Device Research Conference (DRC), South Bend, IN (2017) 1.
[4] T. Matsumoto *et al.*, Scientific Reports **6** (2016) 31585.
[5] T. Makino *et al.*, JJAP **53** (2014) 05FA12.