Simulation of Thermal Effects on Hydrogen-Terminated Diamond MOSFETs

Xi Zhou[1], Frances Williams[1], Sacharia Albin[1] and Kalpathy Sundaram[2]

[1]Engineering Department, Norfolk State University
700 Park Avenue, Norfolk, Virginia 23504, USA
[2]Department of Electrical Engineering and Computer Science, University of Central Florida
Orlando, FL 32816, USA

Hydrogen-terminated diamond (HTD) contains an adsorbate layer at its surface that can generate hole carriers with a high density (10^{13}~10^{14} cm^{-2}) at room temperature.[1,2] The adsorbate appears to have acceptor-like properties with low activation energy. However, the poor thermal stability of the adsorbate layer limits the applications of HTD devices due to desorption below 350K.[3,4] The alternative is to use a passivation layer such as Al_2O_3 thin film that can also serve as a gate insulator produced by atomic-layer-deposition.[5,6] In this paper, we analyze the electrical characteristics of such passivated devices through a two-dimensional device simulation and compare the results with measured data for the temperature range from 140 to 500K. The temperature dependence of basic parameters such as density of states, electron and hole effective masses, intrinsic and extrinsic carrier densities, the saturation velocity and mobility of holes, etc., are studied. In the simulated temperature range, the thermal loss of adsorbates from the passivated device is negligible, and due to a small activation energy (6.147 meV), all adsorbates are ionized[5]. Hence the adsorbate-generated hole density is a constant. To model the temperature dependence of hole mobility, both Coulomb and impurity scattering are considered and their combination causes the temperature coefficient change from positive to negative around 250K, which explains the experimental results quite well[5]. In Fig. 2(a) and (b) the transfer and output characteristics are shown for a device with 400 nm gate length at 300 and 473K that also agree well with the measured data[6]. The maximum drain current at 473K is reduced by 10% of the value at 300K, and the shift in pinch-off voltage is also small, around 0.26 mV/K. This indicates the passivated HTD MOSFETs have stable performance. Since the transconductance of the MOSFETs is mainly controlled by hole mobility (as shown in Fig. 1), its temperature dependence is similar. In addition, the self-heating effect in HTD MOSFET is evaluated and compared with Si MOSFET (Fig. 3). The result suggests that for HTD devices with 200nm gate length, the drain current per unit width can reach up to 1 mA/μm at V_{gs} = -5.5V and V_{ds} = -15V. This is in good agreement with the experimental results for a passivated device[6]. At this high current, however, the increase in lattice temperature is negligible, as small as 30K, due to the high thermal conductivity (25W/(cm K) at T=300K[7]) of diamond. For a similar Si MOSFET, the highest localized lattice temperature can increase by 510K under the same bias conditions, and the drain current may be reduced by 40% from its isothermal value. The ratio of the increase in lattice temperatures for MOSFETs made of Si and HTD is found to be 17:1, which is inversely related to the ratio of their thermal conductivities at 300K. In conclusion, our analysis confirms that a passivated HTD MOSFET device has good thermal stability for its high temperatures applications.

[1]. Hiroshi, Kawarada, Surface Science Reports, vol. 26, pp. 205-259, 1996.
[2]. M. Kubovic, M. Kasu, H, Kageshima, F. Maeda, Diamond and Related Materials, vol. 19, pp. 889-893, 2010.
[3]. A. Denisenko, A. Aleksov, E. Kohn, Diamond and Related Materials, vol. 10, pp. 667-672, 2001.
[4]. M. Kasu, M. Kubovic, A. Aleksov, N. Teofilov, Y. Taniyasu, R. Sauer, E. Kohn, T. Makimoto, N. Kobayashi, Diamond and Related Materials, vol. 13, pp. 226-232, 2004.
[5]. Makoto Kasu, Hisashi Sato, and Kazuyuki Hirama, Applied Physics Express, vol. 5, pp. 025701 1-3, 2012.
[6]. Kazuyuki Hirama, Hisashi Sato, Yuichi Harada, Hideki Yamamoto, and Makoto Kasu, IEEE Electron Device Letters, vol. 33, no. 8, pp. 1111-1113, 2012.
[7]. J. R. Olson, R. O. Pohl, J. W. Vandersande, A. Zoltan, T. R. Anthony and W. F. Banholzer, Physical Review B, vol. 47, no. 22, pp. 14850-14856, 1993.

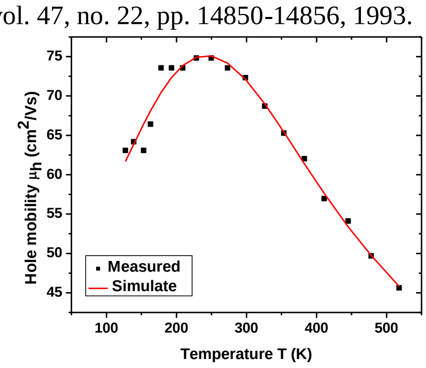

Figure 1. Temperature-dependent hole mobility in passivated HTD. Measured data is from ref.5.

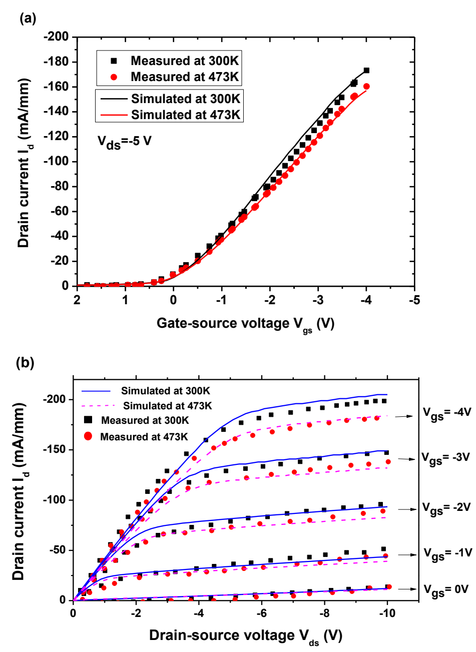

Figure 2. The transfer (a) and output (b) characteristics of HTD MOSFET at 300 and 473 K. $L_g = 0.4\mu m, W_g = 25\mu m$. Measured data is from ref.6.

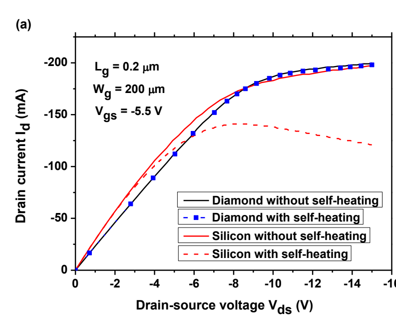

Figure 3. Simulated I_d-V_{ds} curves for HTD and Si MOSFETs with similar structure, with&without the consideration of self-heating effect.