Diamond-Graphite-Diamond Heterostructures Produced by Implantation and HPHT Annealing for Lift-off Transfer and New Devices

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Diamond is very attractive semiconductor material for high power and high frequency micro- and optoelectronics and microelectromechanical systems (MEMS) because it offers wide band gap energy (5.45 eV), high electricbreakdown field (10 MV/cm), high carrier mobility (μ_e = 2000 cm2/V·s; μ_h = 1000 cm^2/V s), high thermal conductivity (22 W/cm·K), hydrophobicity, and hardness [1-2]. But up to now the problem of its doping have not been solved following deep boron acceptor level (E_v+0.32 eV) and even deeper phosphorous donor level (E_c-0.62 eV). Additional difficulties create very low impurity diffusivity and graphitization of implanted regions during high temperature annealing [3]. However, the researches already have demonstrated metal-semiconductor FETs (MESFETs) based on so called "transfer" doping using hydrogen terminated diamond surface for operation at maximal frequencies higher than 50 GHz [4.5]. But long term stability of properties for such transistors is still limited by moderate temperatures ~400^{o}C [5].

To avoid this obstacle we suggest instead of MESFET using the metal-insulator-semiconductor FET (MISFET) with SiC or CN source/drain regions formed by ion synthesis [6]. The advantages of hetero MISFETs are their stability even at operating temperatures higher than 400^{o}C that is impossible in the case of MESFETs. Very high fluences Φ of ions is needed to synthesize S/D regions $\Phi \sim 5{\cdot}10^{17}\,cm^{-2}$. Such fluences even for light ions from H^+ to N^+ lead to amorphisation of diamond layers in the depths in dependence on ion energy [7]. These layers transfer to graphite layers even at HPHT annealing at 4-7 GPa and 1200-1600oC allowing formation of single crystalline membranes with thickness 10 – 1000 nm after electrochemical etching of sacrificial graphite (Fig.1a). Different devices using such membranes and diamond-graphite-diamond (DGD) structures are considered in this report including MEMS membrane sensors (Fig.1b) and integrated photonic crystals for quantum information processing (QIP).

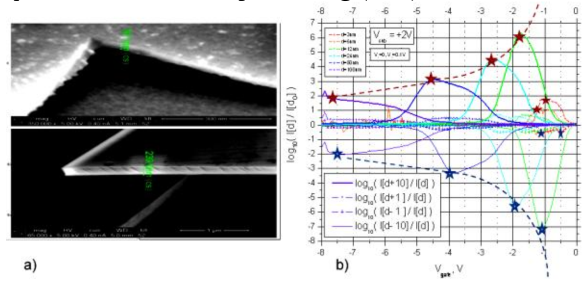

Fig. 1 (a) 30 and 240 diamond membrane; (b) simulated log of membrane FET current relation at ±10 nm membrane gate shift in dependence on gate voltage V_{gate}

Hot (550^{o}C) N^+ ion implantation and even harder HPHT annealing up to 8GPa and 2000^{o}C were used to avoid graphitization and obtain buried n-type CN nanowire in p-type diamond. Calculated current density I_{drain} with different boron doping level for vertical JFET is presented on Fig.2.

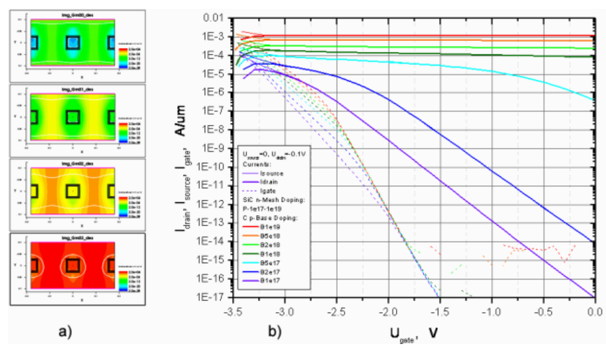

Fig. 2 (a) vertical current flow density through backward biased n-p junction gate; (b) simulated log of membrane FET current relation at ±10 nm membrane gate shift in dependence on gate voltage V_{gate}

Current density I_{drain} in the heterostructure JFET is equal to 50 mA/mm at V_g=-3V at optimal doping level of p-base $2{\cdot}10^{17}\,cm^{-3}$. This current is about three order of magnitude higher than that for all-diamond based JFET with highly doped n^+/p^+ fins [8].

Few examples of using DGD structures is also considered for spin state control of color centers in diamond nanostructures.

[1] I. Akimoto et al., APL, 105 (2014) 032102
[2] J.R. Olson, et al., Phys. Rev. B 47 (1993) p.14850
[3] J.F. Prins. Diamond Relat. Mater. 11 (2002) p.612
[4] S. Russell et al., IEEE TED, 62 (2015) p.751
[5] H. Kawarada et al. Sci. Rep. 7 (2017) 42368
[6] V.P. Popov et al. ICMNE-2016 Proc. p.149
[7] V.P. Popov et al. Int. J. Nanotechnol. 12 (2015) p.226
[8] T. Iwasaki et al. JEDS, 5 (2016) 2624301