Simulation of a Voltage Controlled Resistor Mimicking the Geometry of a MOSFET Device having Graphite Channel

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Abstract: A voltage controlled resistor (VCR) is simulated by replacing the semiconductor channel of a MOSFET device with graphite and embedding Si nanoparticles near the insulator-channel interface. The change in output drain current is found to depend on the thickness and relative permittivity of the insulator film together with the loading of Si nanoparticles. A material with higher dielectric permittivity, for example, graphene oxide as insulator layer is found to generate a larger change in the output current. Further, increasing concentration of the Si nanoparticles in the channel is found to increase the change in current for constant gate voltage.

Keywords: Semiconductor, Graphite, Insulator, MOSFET.

1. Introduction:

Paper-based microelectronic devices [1-3] have attracted attention in recent times because of the simplicity in fabrication and cost effectiveness. In this direction, graphite based devices are also very strong contenders to make their mark in the domain of flexible electronics [4-6]. Recent studies report the fabrication of paper-based FET devices using graphite as the channel [1, 2]. Further, graphene based FET devices have also been reported [7]. These studies indicate that the next generation devices are supposed to integrate the simplicity of the paper based devices alongside exploiting the graphitic properties in a single framework. Herein we show the response of a paper-based voltage controlled resistor (VCR) in which the semiconductor channel of a MOSFET device is replaced by graphite and Si nanoparticles are embedded near the insulator-channel interface as shown in figure 1(a). The study is performed by simulating the system in the commercial software COMSOL multiphysics using finite volume method. The change in output drain current is found to depend on the thickness and relative permittivity of the insulator film together with the loading of Si nanoparticles. Interestingly, insulators like graphene oxide with higher dielectric permittivity is found to generate a larger change in the output current. Further, increasing the concentration of the Si nanoparticles in the channel is found to increase the change in current for constant gate voltage. The results are described in figure 2 & 3.

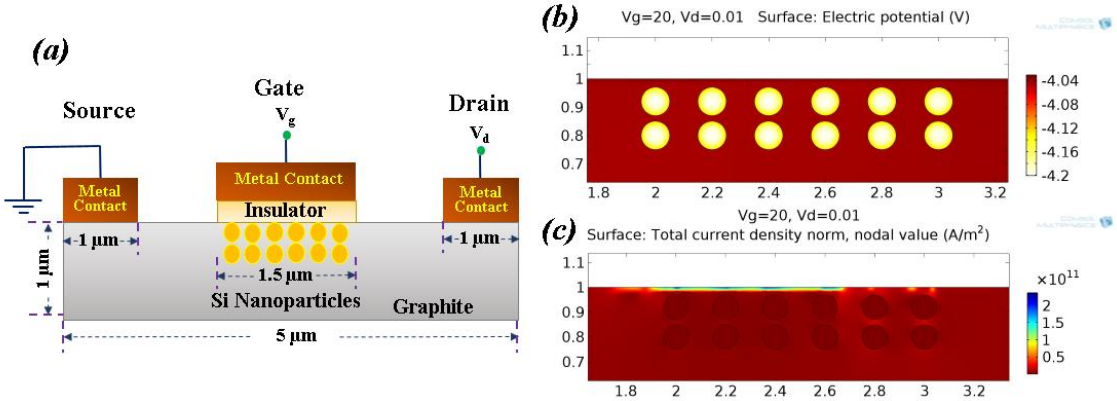

Figure 1: (a) Schematic diagram of the device, and the plots of (b) surface electric potential (V) and (c) surface total normalized current density (A/m^2) in the channel region

2. Use of COMSOL Multiphysics:

In this study, we used the semiconductor module to study the DC characteristics of the device. The device geometry is similar to MOSFET as shown in figure 1(a), where the device is made of graphite channel. Two metal contacts are used as source and drain terminals and the third metal contact as gate placed in between source and drain is separated from the channel by a thin layer of dielectric such as graphene oxide.

3. Governing equations:

The semiconductor module solves Poisson's equation for the charge carriers. The Eq. 1 defines the Poisson's equation in which the electric field term is shown at the left hand side where ε_r and V denotes dielectric constant and voltage respectively and space charge densities are shown at the right hand side where q is the charge of carrier and electron and hole surface concentration is denoted by n and p respectively. N_A^- and N_D^+ are the acceptor and donor ion concentration.

$$\nabla.(\varepsilon_r \nabla V) = q(n - p + N_A^- - N_D^+)\,. \qquad (1)$$

The following electron and hole continuity equations (Eqs. 2 and 3) also solved along with the Poisson's equation where J_n and J_p are the current for electrons and holes respectively. U_n and U_p are the recombination rate of electrons and holes.

$$\frac{1}{q}\nabla.J_n = -U_n\,, \qquad (2)$$

$$\frac{1}{q}\nabla.J_p = U_p\,. \qquad (3)$$

The Eqs. 1 – 3 are solved using finite volume method which implicitly conserved current with Scharfetter-Gummel discretization. The current is defined with drift diffusion equations with Fermi-Dirac carrier statistics and were solved for the carriers. Here E_C denotes the conduction band energy and electron and hole mobility are denoted by μ_n and μ_p.

$$J_n = (\mu_n \nabla E_c + \frac{qD_{n,th}}{T}\nabla T)n + \mu_n k_B T G(n/N_C)\nabla n\,. \qquad (4)$$

$$J_p = (\mu_p \nabla E_c - \frac{qD_{p,th}}{T}\nabla T)p - \mu_p k_B T G(n/N_V)\nabla p\,. \qquad (5)$$

In semiconductor interface boundary conditions, the terminal is taken as voltage source with ohmic contact. Electrical insulation is assumed throughout device boundary other than the terminals.

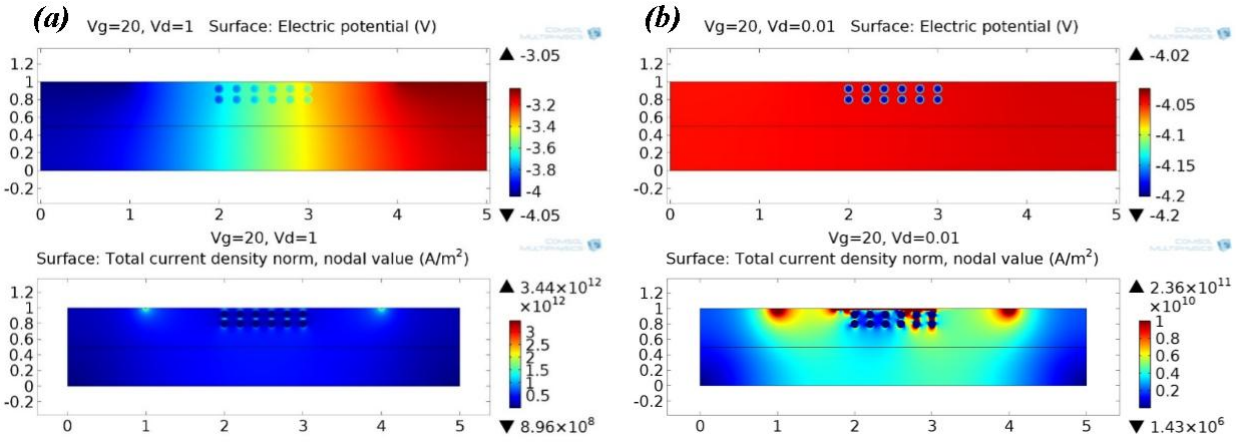

Figure 2: Surface electric potential (V) plot and Surface total normalized current density (A/m^2) plot for (a) V_d = 1 V, (b) V_d = 10 mV where $\mathcal{E}_r$ = 100 and dielectric thickness is 1 µm.

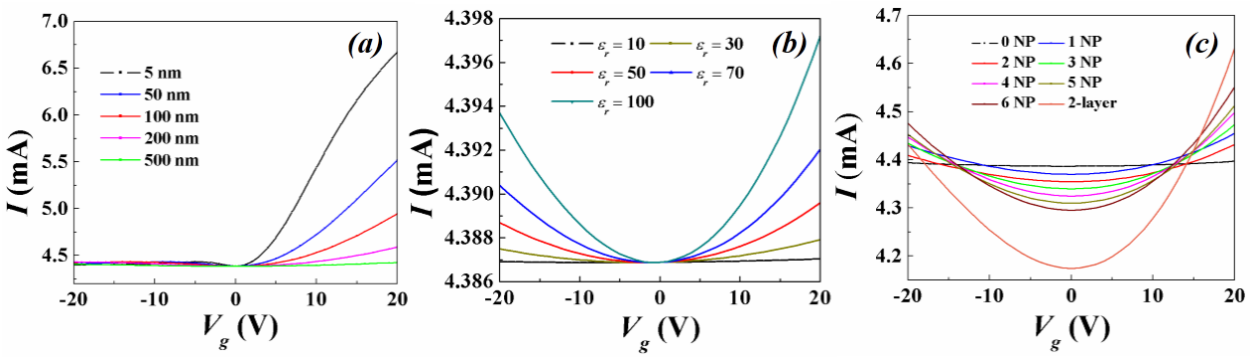

Figure 3: Drain current versus gate voltage for different (a) dielectric thickness values with $\mathcal{E}_r$ = 100 (b) relative permittivity of dielectric material with thickness 1µm (c) nanoparticle loading with $\mathcal{E}_r$ = 100 and dielectric thickness is 1 µm. In all the cases drain voltage is kept fixed at 10 mV.

4. Results and Discussion:

The surface potential distribution and surface current density distribution is shown in figure 2. A small potential difference is observed around nanoparticles from figure 2(a) and (b). The current density distribution for 10 mV is shown in figure 1(c) but to show the distribution in the whole device few data at the interface are compromised in case of figure 2(b). In figure 3(a) the change in drain current with gate voltage is shown for different thicknesses of dielectric layer. It is found that for positive gate voltage, the change in current is high and increases with decreasing the thickness of the gate dielectric layer whereas the change in current for negative gate voltage has negligible effect on the drain current. Figure 3(b) shows the output characteristics of the device with different values of relative permittivity of the dielectric layer. From the graph it is clear that the change in current increases with increasing relative permittivity of the dielectric material. The change in resistance becomes more significant when Si nanoparticles are embedded in the channel region. The change in current increases when number of nanoparticles in the channel increases as shown in figure 3(c). In all the cases drain voltage was kept fixed at 10 mV.

5. Conclusions:

In this study, graphite has been used as the channel material in the geometry of a MOSFET device and the effect of variations in dielectric layer thickness, relative permittivity and nanoparticle loading on I-V characteristics of the device has been presented. It has been observed that a minimum drain current exists without gate voltage but an applied gate voltage changes the conductance of the channel region. In conclusion the device works as a voltage controlled resistor where the conductance or resistance of channel is a function of gate voltage.

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7. References:

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