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Potential speed of a diamond field-effect transistor on subsurface two-dimensional hole gas

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It is shown that the significant change of hole mobility in a two-dimensional hole gas under H-terminated surface of artificial diamond by the variation of a strong orthogonal electric field detected lately can be used for the creation of a high-speed diamond field-effect transistor. According to calculations made for realistic parameters of such a device the time of more than 50% modulation of source-drain current by gate voltage rapidly decreases with the increase of the hole sheet density in the subsurface conduction channel formed by this gas and for its value $7 \cdot 10^{13}$ cm^{-2} achieves 7 ps

Keywords: diamond, high-speed field-effect transistor, mobility.

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1. Introduction

The unique properties of artificial diamond (high thermal conductivity, electrical strength, radiation and chemical resistance, etc.) make it a promising material for modern electronics and optoelectronics [1,2]. However, it is difficult to obtain a sufficiently high and uniform conductivity in artificial diamond, which hampers its practical application. The traditional route (doping) is fraught with major challenges arising due to high (exceeding significantly the thermal energy at room temperature) activation energies of doping impurities and the difficulty of their incorporation into the diamond crystal lattice [1]. This is the reason why the formation of hole-type conducting layers at the surface of undoped diamond coated with hydrogen atoms has attracted considerable attention [1].

The diamond field-effect transistor with a two-dimensional hole gas is one of the most important applications of such layers [1]. The speed of operation of this device is essential for its application. According to the standard theory of such devices [3], current modulation in them is achieved by enriching (depleting) the gate region with charge carriers via the adjustment of gate voltage. The time it takes for a transistor to switch from an „on“ state to an „off“ state and back cannot be shorter than the time of propagation of these carriers throughout the length of the gate region [3]. Therefore, one needs to reduce this length to enhance their speed performance, and such measures are not always technologically simple and efficient.

However, it has recently been demonstrated experimentally [4] that the energy of the Rashba spin-orbit interaction of holes with the asymmetric potential of the crystal lattice near the surface and their mobility vary significantly when a strong orthogonal electric field with a strength on the order of the breakdown magnitude for diamond (10 MV/cm) applied to a diamond surface coated with hydrogen atoms is altered. It is important to note that the characteristic times of these variations are in no way related to the time it takes for holes to pass through the region of application of this field. Instead, they are determined by the time of restructuring of their wave functions transverse to the surface that results in the holes approaching to (or moving away from) this surface and, consequently, strengthening (or weakening) of its influence on them (e.g., their scattering off surface hydrogen atoms, defects, and roughness may become more or less intense). Since the thickness of the hole layer characterized by these functions is very small ($\sim$ 1 nm, which is just several times higher than the lattice constant of diamond [4]), this time (an order-of-magnitude estimate of which is the ratio between the thickness of this layer and 10^7 cm/s (the maximum transport velocity of holes in diamond with a strong electric field applied to it), which amounts to 10 fs) is very short and negligible in comparison with all the times considered below.

2. Model of a diamond field-effect transistor

The present study is focused on the calculation of the characteristic time of current modulation in a two-dimensional near-surface hole gas when the hole mobility is altered by a strong orthogonal variable electric field.

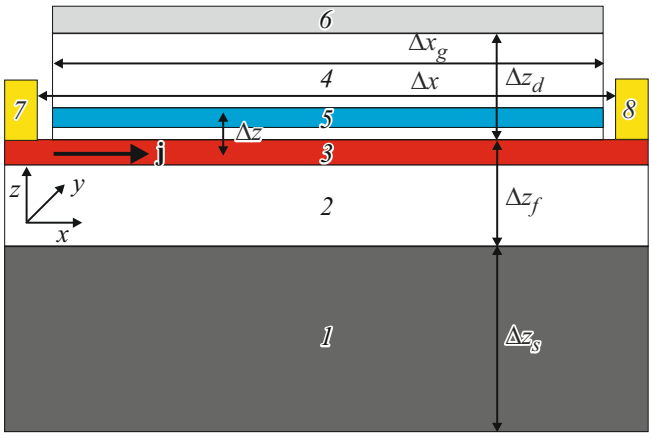

Figure 1. Model of a diamond field-effect transistor and the coordinate system used: *1* — *p*-type diamond substrate with thickness Δz_s grown at high pressure and temperature and doped heavily with boron, *2* — vapor-deposited film of undoped diamond with thickness Δz_f, *3* — two-dimensional hole gas under the surface coated with hydrogen atoms, *4* — electrically strong dielectric (e.g., undoped diamond) with thickness Δz_d, *5* — negative charge layer at its surface located at distance Δz from the two-dimensional hole gas, *6* — gate (e.g., Al), *7* — source (e.g., Ti/Au), and *8* — drain (e.g., Ti/Au). The source–drain distance is Δx, and the gate has length Δx_g and is positioned symmetrically relative to the source and the drain. Since the sample is considered to be homogeneous along the *y* axis, the current density and the electric field are zero in this direction. (A color version of the figure is provided in the online version of the paper).

Calculations were carried out for the model of a diamond field-effect transistor based on this effect (see Figure 1).

We assume that a vapor-deposited film of undoped diamond is grown on the surface of a *p*-type diamond substrate doped heavily with boron atoms. A layer of an electrically strong dielectric material (e.g., undoped diamond) with a static permittivity of the same order of magnitude as the static permittivity of diamond ($\varepsilon = 5.7$) is applied to the surface of this film coated with hydrogen atoms. A two-dimensional hole gas forms under the surface of the diamond film coated with hydrogen atoms, and a layer of negative charge with a uniform and time-independent sheet density n_0 forms in the dielectric above the surface of the diamond film. A gate electrode is positioned on the surface of the dielectric, and source and drain electrodes occupy parts of the diamond film surface left without the dielectric coating. The orthogonal electric field applied to the two-dimensional hole gas is altered by varying the potential difference between the substrate and the gate.

To determine the time dependence of source–drain current under a varying potential difference between the diamond substrate and the gate, the continuity equation was solved for sheet density p of the two-dimensional hole gas that depends on time t and the coordinate along axis x directed from the source to the drain within the plane of the gas layer:

$$\frac{\partial p}{\partial t} = -\frac{1}{e}\frac{\partial j}{\partial x}. \tag{1}$$

Here, $j = e\mu E p - ed\frac{\partial p}{\partial x}$ is the density of current directed along axis x per unit length along y; e is the hole charge, which is equal to the elementary charge; μ is the hole mobility; E is the projection of the electric field onto axis x; and d is the diffusion coefficient tied to μ by the Einstein relation [5], which follows from the condition of zero current for a thermodynamically equilibrium distribution of holes and takes the following form for a degenerate two-dimensional hole gas considered below: $d = \mu E_F/e$, where $E_F = \pi\hbar^2 p/m$ is the Fermi energy in the two-dimensional case, $\hbar$ is the Planck constant, and m is the effective hole mass, which is assumed to be equal to the mass of a free electron in the estimates obtained below. The mobility is tied to relaxation time τ of hole quasi-momenta by well-known formula $\mu = e\tau/m$ [5].

The projection of the electric field onto axis x is

$$E = \frac{2e}{\varepsilon}\int_0^{\Delta x}\frac{p(t,x')}{x-x'}dx' - \frac{2e}{\varepsilon}n_0\int_0^{\Delta x}\frac{x-x'}{(x-x')^2+(\Delta z)^2}dx' + \tilde{E}, \tag{2}$$

where the first two terms correspond to the superpositions of fields from infinitely thin and long (along axis y) „threads“ with charge densities per unit length equal to $ep(t,x')dx'$ and $-en_0dx'$, respectively, and uniform field $\tilde{E}$ is set at any specific time in such a way as to maintain the equality of potential difference $u = -\int_0^{\Delta x} Edx$ between the drain and the source to constant value u_0 specified by an external voltage source. The influence of charges induced at the upper boundary of the heavily doped diamond substrate and the lower boundary of the gate by varying the potential difference between them on the x-projection of the electric field may be neglected, since their contributions are characterized by formulae similar to the second term in (2) with n_0 and Δz replaced by the sheet densities of these charges and Δz_f and Δz_d, respectively. Since these sheet densities are of the same order of magnitude as n_0 and Δz_f, $\Delta z_d \gg \Delta z$ (see below), these contributions are small compared to the contribution from the negative charge layer in the dielectric introduced by the second term in (2).

The time and coordinate dependence of the hole mobility was modeled by the following function:

$$\mu = \begin{cases} \frac{e\tau_1}{m}, & 0 < x < \frac{\Delta x}{2} - \frac{\Delta x_g}{2},\ \frac{\Delta x}{2} + \frac{\Delta x_g}{2} < x < \Delta x, \text{ all } t, \\ \frac{e\tau_1}{m}, & \frac{\Delta x}{2} - \frac{\Delta x_g}{2} < x < \frac{\Delta x}{2} + \frac{\Delta x_g}{2},\ t < 0,\ \Delta t < t, \\ \frac{e\tau_2}{m}, & \frac{\Delta x}{2} - \frac{\Delta x_g}{2} < x < \frac{\Delta x}{2} + \frac{\Delta x_g}{2},\ 0 < t < \Delta t, \end{cases} \tag{3}$$

where 0 is the moment when voltage is applied between the gate and the heavily doped diamond substrate, Δt is the

moment when this voltage is switched off, and $\tau_2 < \tau_1$ due to the fact that holes are brought closer to the diamond surface by the applied electric field and the intensity of their scattering off surface hydrogen atoms, defects, and roughness then increases accordingly.

The equality of p at the source and the drain (i.e., at $x = 0$ and $x = \Delta x$) to a given time-independent value p_0 was used as boundary conditions for Eq. (1). The initial condition was set at a certain negative point in time (i.e., before the voltage between the gate and the heavily doped diamond substrate was switched on) chosen arbitrarily, since the steady-state distribution of holes prior to the application of voltage was taken as this condition. The latter distribution was found as a solution to equation $-\frac{1}{e}\frac{\partial j}{\partial x} = 0$ with the mobility maintained prior to switching the voltage on, the boundary conditions indicated above, and constant potential difference u_0 between the drain and the source.

The following values of the above parameters were chosen for modeling: $\Delta z_s = 1000\,\mu$m, $\Delta z_f = 5\,\mu$m, $\Delta z_d = 5\,\mu$m, $\Delta z = 0.1\,\mu$m, $\Delta x = 10\,\mu$m, $\Delta x_g = 8\,\mu$m, $u_0 = -1$ V, and, following [4], $\tau_1 = 7.6$ fs and $\tau_2 = 2.8$ fs.

3. Results and discussion

The simulation revealed that the distributions of sheet density of holes p along axis x are close to a uniform distribution with the value of p_0 at all times in all the examined cases. Therefore, this value may be regarded as the characteristic one for p. Figure 2 presents the dependences of j at the drain point (i.e., at $x = \Delta x$) on time for various $p_0 = n_0$. Time Δt in Figure 2, c is reduced compared to the one in Figures 2, a and b for clarity only, since the time needed for the current density to reach steady-state levels at fixed voltages between the gate and the heavily doped diamond substrate in Figure 2, c is significantly shorter than in Figures 2, a and b.

It follows from Figure 2 that the current switching time is ~ 50 ps at a relatively low sheet density of holes $p \sim 10^{13}\,\mathrm{cm}^{-2}$. However, as the density grows, this time decreases quickly (approximately inversely proportional to it) and reaches the value of ~ 7 ps at $p \sim 7 \cdot 10^{13}\,\mathrm{cm}^{-2}$. The current modulation depth exceeds 50% in all cases, which is quite sufficient for efficient operation of a field-effect transistor (the constant current component may be filtered out of the output signal by a capacitive filter).

It should be noted that the determined current switching times are much shorter than the time it takes for holes to pass through the gate region, which is estimated as the ratio of length Δx_g of this region to characteristic hole velocity $j/(ep)$ in it and assumes a value of several hundred nanoseconds in all the examined cases. These switching times are set by the times of formation and relaxation of regions of increased and reduced sheet density of holes that form at the left and right boundaries of the gate space, respectively, when the voltage between the gate and the heavily doped diamond substrate is switched (see Figure 3).

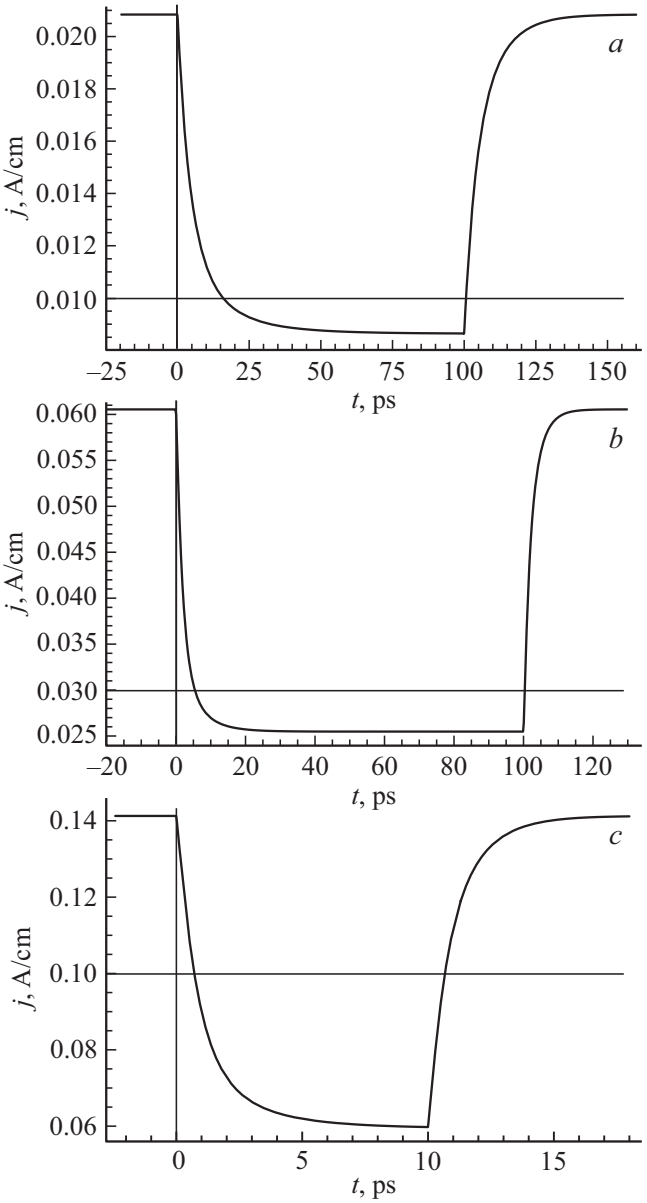

Figure 2. Dependence of the electric current density per unit length along axis y in a two-dimensional hole gas on time for $\Delta t = 100$ ps and $p_0 = n_0 = 1 \cdot 10^{13}\,\mathrm{cm}^{-2}$ (a), $\Delta t = 100$ ps and $p_0 = n_0 = 3 \cdot 10^{13}\,\mathrm{cm}^{-2}$ (b), and $\Delta t = 10$ ps and $p_0 = n_0 = 7 \cdot 10^{13}\,\mathrm{cm}^{-2}$ (c).

Since the variations of density in these regions are very small compared to the corresponding steady-state values ($\sim 0.01\%$ for $p_0 = n_0 = 7 \cdot 10^{13}\,\mathrm{cm}^{-2}$), this time is also short.

It should also be noted that a heavily doped diamond substrate with boron atom density $N_b \cong 5 \cdot 10^{20}\,\mathrm{cm}^{-3}$ undergoes a phase transition to a state with metallic conductivity at room temperature [6], as a result of which all boron atoms become ionized and the density of free carriers (holes) becomes equal to N_b. With their mobility being $\mu_s = 3.6\,\mathrm{cm}^2/(\mathrm{V}\cdot\mathrm{s})$ [7], the resistivity of such a

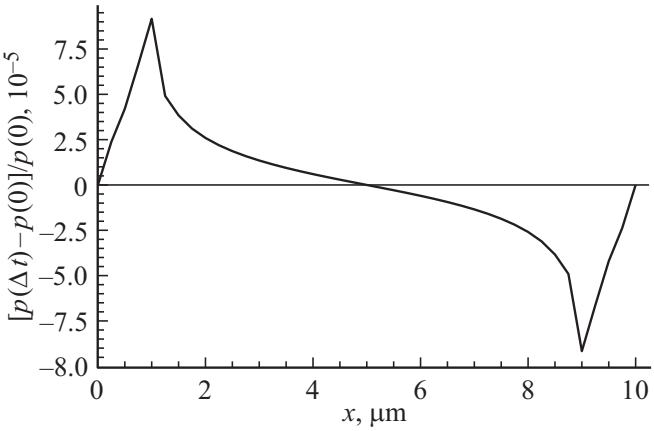

Figure 3. Dependence on coordinate x of the difference between hole sheet densities after $(p(\Delta t))$ and before $(p(0))$ the application of voltage between the gate and the heavily doped diamond substrate (normalized to $p(0)$) for $\Delta t = 10\,\text{ps}$ and $p_0 = n_0 = 7 \cdot 10^{13}\,\text{cm}^{-2}$.

substrate is low: $\rho_s = 1/(e\mu_s N_b) \cong 3.5\,\text{m}\Omega \cdot \text{cm}$. Therefore, the recharge time the capacitor forming between the upper boundary of this substrate and the lower boundary of the gate, needed to vary the potential difference between them (i. e., alter the orthogonal electric field applied to the two-dimensional hole gas) is also quite short. It is equal to the product of substrate resistance R and capacity C of this capacitor (i. e., $RC = \varepsilon\rho_s \Delta z_s/[4\pi(\Delta z_f + \Delta z_d)] \cong 0.17\,\text{ps}$). This time is significantly shorter than the shortest of the current switching times determined above. Therefore, the orthogonal electric field applied to the two-dimensional hole gas may be adjusted at a rate that is sufficient to implement these current switching times.

4. Conclusion

Thus, the potential operation speed of a field-effect transistor with a conducting channel based on a two-dimensional hole gas formed near a diamond surface coated with hydrogen atoms achieved by varying a strong ($\sim 10\,\text{MV/cm}$) orthogonal electric field applied to this gas in the gate region may reach $1/7\,\text{ps}^{-1} = 140\,\text{GHz}$ with a current modulation degree of $> 50\%$. This value is significantly higher than those demonstrated earlier in diamond field-effect transistors [8–10] and is on par with the best performance figures reported for such devices based on other semiconductor materials [11–15].

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Conflict of interest

The authors declare that they have no conflict of interest.

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