Phase inversion of THz radiation from silicon nanostructures

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Abstract. The experimental data of the optical and electric features of the silicon nanosandwiches obtained by silicon planar technology in the frameworks of the Hall geometry are presented. Silicon nanosandwiches represent the ultra-shallow silicon quantum wells of 2 nm wide that are confined by \(\delta\)-barriers heavily doped with boron, which appear to be used as the phase invertors and modulators of optical THz spectra and electric signals. The negative-U dipole boron centers formation, which appear to confine the edge channels, results in the effective mass dropping and corresponding reduction of the electron-electron interaction thereby giving rise to the macroscopic quantum phenomena at high temperatures up to room temperature. The modulation phase shift of the THz electroluminescence spectrum and phase control of the longitudinal conductance are observed by changing either the magnitude of the source-drain current or the voltage applied to the external gates of the silicon nanosandwiches within the quantum Faraday effect.

1. Introduction

The problem due to the fabrication of compact and tunable far infrared and terahertz (THz) radiation sources [1 – 5] and detectors [6] with the controlled parameters such as frequency, amplitude and phase seems to be one of the main unresolved problems of current interest in optical technology. However, using silicon planar technology, the silicon nanosandwich-structures that appeared to be prepared in the frameworks of the Hall geometry are of particular interest as emitters and recorders of THz radiation [7, 8], as well as various devices such as the phase invertors and modulators of optical spectra. These silicon nanosandwiches represent the ultra-shallow silicon quantum well of 2 nm wide that is confined by \(\delta\)-barriers heavily doped with boron on the surface of n-type Si (100) wafer [9] (figure 1). The high concentration of boron inside the \(\delta\)-barriers which equals to \(N(B) = 5 \cdot 10^{21} \text{sm}^{-3}\) gives rise to the formation of the negative-U dipole boron centers \(2B^0 \rightarrow B^+ + B^-\). Moreover, the negative-U centers mark the high mobility edge channels with the significant reduction of the electron-electron interaction [10]. In addition to the dropping an effective mass of carriers to such values as \(m^* \approx 2 \cdot 10^{-5} m_e\) [11] the electron-electron interaction reduction inside edge channels causes the observation of macroscopic quantum phenomena [10] such as conductance quantization at the high temperatures up to room temperature [12]. Besides, these properties of silicon nanosandwich allow the THz emission observation due to the quantum Faraday effect under the condition of the reduction of the dissipation processes. Here, we present the findings on the interplay between optical and electrical phase transport characteristics in silicon nanosandwich.
2. Modulated THz electroluminescence

The presence of the constant external voltage of the p-n junction results in the spin-orbital splitting in the edge channel in case of the source-drain current appearance. Topological and superconducting features of the edge channel were proved by the quantum spin Hall effect measurements [13] and the multiple Andreev reflection [14] respectively.

![Figure 1. Silicon nanosandwich-structure.](image)

The reason of the modulated THz electroluminescence observation could be described using the Josephson effect. Until the source-drain current value $I_{ds}$ is less than some critical current value $I_{cr} \approx e/\tau$ the electron-electron interaction between single carriers inside the edge channel is strongly reduced. However, if $I_{ds} > I_{cr}$, then modulated THz electroluminescence which is dependent on the $I_{ds}$ value is revealed by the optical spectra. Moreover, the reduction of the electron-electron interaction appears to provide the cooling effect as the red shift phenomena, which is dependent on the source-drain current value [10, 12], with the phase control and the modulation of the electroluminescence spectrum by varying the source-drain current on the one hand (figure 4) and either the lateral gate voltage $U_{xy}$ (figure 2) or the top gate voltage $U_g$ (figure 3) on the other hand.

3. Fractional conductance quantization

The properties of the electric signals and current-voltage characteristics of the edge channel which demonstrate the quantum interference processes confirm the background of the optical properties mentioned above. The current-voltage characteristics of the edge channels of silicon nanosandwiches exhibit the fractional quantization of the longitudinal conductance, which is dependent on the magnitude of the stabilized source-drain current $I_{ds}$ as the quantizing parameter on the one hand and the lateral gate voltage $U_{xy}$ applied to the Hall contacts as the control parameter on the other hand (figure 5a). The presence of the stabilized source-drain current results in the appearance of the
magnetic field induced by the system of non-interacting carriers and proportional to the magnitude of the source-drain current according to the harmonic oscillator model.

![Figure 2](image.png)

**Figure 2.** The phase control and the modulation of the electroluminescence spectrum in dependence on the lateral gate voltage $U_{xy}$ applied to the Hall contacts.

Besides, the magnetic field induced by the source-drain current results in the appearance of the diamagnetic current $I_{dia}$, which is not involved in the charge transfer, but in case of the voltage applied to the lateral gates is capable to effect on the magnitude of the longitudinal conductance within the quantum Faraday effect. Owing to the above noticed, the significant reduction of the electron-electron interaction appears to provide the process of the single magnetic flux quanta capture on the system of non-interacting carriers in the edge channel within the frameworks of the Laughlin model [12, 15, 16]. Thus, by varying the value of the voltage applied to the lateral gate, the phase shift in the Aharonov–Bohm effect,

$$G = G_0(I_{ds}, U_{xy}) \cdot \cos^2(\frac{\pi \Phi'}{2 \Phi_0}),$$

(1)

can be created [17]. The total magnetic flux $\Phi' = \Phi + \Delta \Phi$, which determines the conductance phase, depends both on the magnitude of the source-drain current, $\Phi = \alpha I_{ds}$, and on the value of the lateral gate voltage, $\Delta \Phi = -eU_{xy}/I_{dia}$, with the linear dependence of the diamagnetic current on the source-drain current

$$I_{dia} = I_{dia}(I_{ds}) = \gamma I_{ds}.$$  

(2)

The legitimacy of the formula used is determined not only by its agreement with experimental data obtained ($\alpha = 4.32 \cdot 10^{-5}$ Wb/A, $\gamma \approx 6 \cdot 10^{-4}$), but also by the maximum value of the longitudinal...
conductance, which is about three percent of the conductance quantum value $G_0 = e^2/h$, which is evidence of the weak coupling regime in the edge channel of silicon nanosandwich (figure 5b).

Figure 3. The phase control and the modulation of the electroluminescence spectrum in dependence on the top gate voltage $U_g$. 
Figure 4. The phase control and the modulation of the electroluminescence spectrum in dependence on the source-drain current value $I_{ds}$.

Figure 5. The current-voltage characteristics of the edge channels of silicon nanosandwiches, which is dependent on the magnitude of the stabilized source-drain current $I_{ds}$ as the quantizing parameter on the one hand and the lateral gate voltage $U_{xy}$ applied to the Hall contacts as the control parameter on the other hand.

4. Conclusion
In summary, the presented correspondence of the THz electroluminescence spectrum with the phase characteristics of the longitudinal conductance of the edge channels of silicon quantum nanosandwich of the same structure determine the legitimacy of their interpretation within the quantum Faraday effect, with the ability of phase and modulation control by either the source-drain current or the external gates voltage changing. Finally, the modulated phase shift that is observed in the electroluminescence spectra is in a good agreement with the phase characteristics revealed by the longitudinal conductance as a function of the lateral gate. Thus, the phase invertors as well as the optical or signal modulators, which are based on silicon nanosandwiches, seem to be obtained.

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