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Majorana-interaction Impact on Collapse States in Graphene p-n Junctions

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Abstract. The confinement of vortex topologically-nontrivial graphene charge carriers in a hexagonal graphene p-n-junction region under an action of an external electrostatic superlattice potential has been investigated. The existence of steady atom-like localized bound Majorana states and confinement of collapse states through Majorana resonances of Klein scattering are demonstrated

Keywords: Majorana interaction, collapse state, graphene, quantum dot, confinement

Introduction. Electrostatically confined graphene quantum dots (GQD) being p-n graphene junctions, are considered nowadays as a promising system for robust quantum computing primarily due to topological non-triviality of the k-space. It has been shown [1], that electronic properties such as local density of states, atom-like behaviour and the existence of the so called quasi-zero energy band can be accurately described with the use of the quasi-relativistic theory of graphene [2]. Recently, we have proposed quasi-relativistic quantum field model of graphene [3] and demonstrated that quasi-particle excitations in the model are Majorana-like fermions rather than Dirac ones. The last means that non-Abelian statistics of these charge carriers can give additional gain for system stability and this will be the goal of the paper.

Methods and materials; results. A Hamiltonian, H_{GQD} , of the GQD model reads $H_{\text{GQD}} = H_{\text{M}} + V$, where H_{M} is a quasi-relativistic Hamiltonian of pseudo-Majorana graphene model [3], V is a pseudopotential [1]. Wave functions of GQD being hexagonally symmetrical belong to the states of the graphene superlattice that is formed under an action of electrically polarized substrate. Eigenstates of the quantum dot should satisfy the periodical boundary conditions imposed by the existence of the superlattice on the wave vectors $\vec{k}$. For the case of GQD of torus topological class [2], they are as follows:

$$(2n_1 + 1)(\vec{A}_1 \cdot \vec{k}) = 2\pi m_1, (2n_2 + 1)(\vec{A}_2 \cdot \vec{k}) = 2\pi m_2,$$

where m_1, m_2 are integer, $\vec{A}_1$ and $\vec{A}_2$ are two basis vectors of the rhombic unit supercell.

Eigenenergies $\varepsilon_{i,\text{GQD}}$ for graphene state corresponding to these found wavevectors $\vec{k}_{i,\text{GQD}}$, have been found by mapping their to the reduced graphene

Brillouin zone. The eigenfunctions of GQD were searched by using a series expansion in bispinor Bloch plane wave functions $\Psi_{\vec{k}_{j,GQD}}(\vec{r}) \exp(i(\vec{k}_{j,GQD} \cdot \vec{r}))$ of graphene pseudo-Majorana vortex particles possessing the wave vector $\vec{k}_{j,GQD}$ and the energy $\varepsilon_{j,GQD}$. Here $\Psi_{\vec{k}_{j,GQD}}(\vec{r})$ is the solution in momentum representation for the pseudo-Majorana single-particle excitation in the quasi-relativistic graphene model without the pseudopotential V . Eigenproblem has been solved for linear combinations of forty constructed basis Bloch functions with found $\vec{k}_{i,GQD}$ and $\varepsilon_{i,GQD}$. These forty base functions have been chosen in few ways: 1) with the smallest $\varepsilon_{i,GQD}$, 2) with the highest $\varepsilon_{i,GQD}$, 3) with the smallest norm of $\vec{k}_{i,GQD}$. Box normalization conditions have been used for the eigenstates.

Results. Figure 1 shows the norm of the wave function of graphene p-n junction for a representative localized atomic-like state of the quantum dot. In this case, the localization is stipulated by a constructive interference of wave functions.

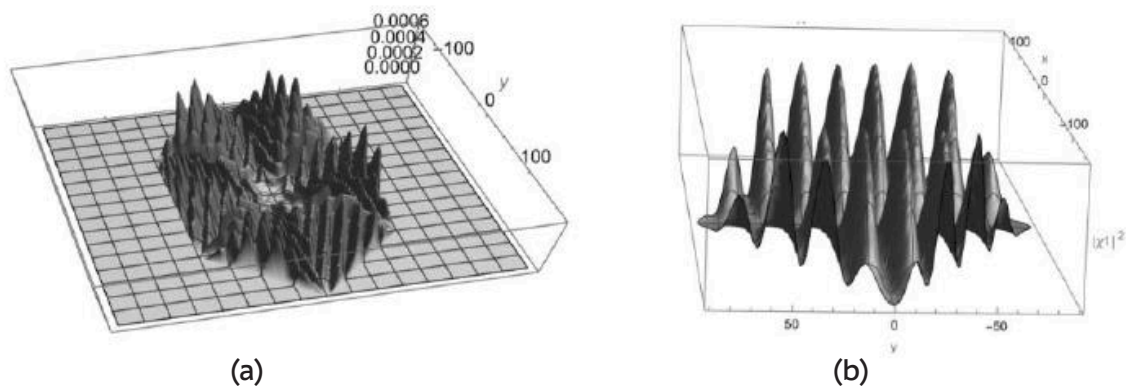


Fig. 1. Norm of the hole (electron) wave function of the hexagonal p-n junction (a) consisting of three unit cells of superlattice and the norm of the hole(electron) wave function in the supercell (b). This atom-like state corresponds to the energy level 0.933 eV

A localized atom-like GQD state can appear as a Klein scattering resonance in a process of scattering of the Dirac pair consisting of bound Majorana particles. This state is presented in Figure 2a. The fact that this state is the Klein resonance is proven by its free passing through the potential barrier at normal incidence on the supercell boundary for phases which are multiples of $\pi \pm 2\pi n$; $n = 0, 1, \dots$ [4] as Inset to the figure 2a shows. The bound states of two Majorana-like particles represent themselves hole (electron) states possessing a total zero topological charge and with the hexagonal symmetry as shown in Figure 2a.

The pseudo-Majorana free state of the electrostatically confined graphene quantum dot is a superposition of vortex states possessing non-zero topological charges. Since the total topological charge of the states is non-zero, the wave function of such a superposition has the electron-hole symmetry, as can be seen in the

inset to Figure 2b. The electron-hole symmetry is an evidence that the Majorana configuration is electrically neutral. These Majorana-like states are wave packet of high-frequency (low-frequency) states with amplitude low-frequency (high-frequency) modulation.

The translational symmetry of the high-frequency states with a high value of the GQD wave vector $\vec{q}_h \equiv \vec{k}_{i,GQD}$, $\vec{q}_h \gg 1$ is distorted by the superlattice potential due to the addition of a small basis wave vector $\vec{Q}$, $\vec{Q} \ll \vec{q}_h$ of the superlattice unit cell to $\vec{q}_h$.

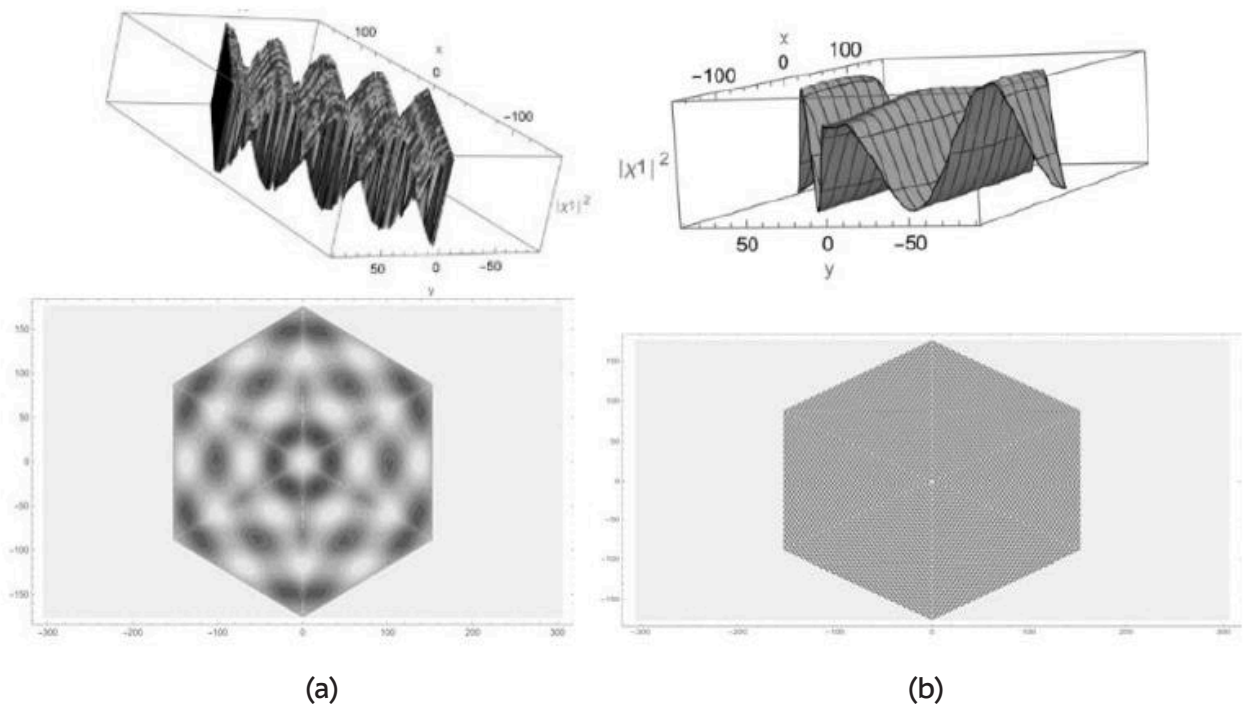


Fig. 2. Contour plots for the norm of hole (electron) (a) and pseudo-Majorana (b) states of the hexagonal p-n junction; energies of the states are of 0.313 and 0.059 eV, respectively. The norm of the wave functions in the unit cell of superlattice are shown in Insets to the figures 2(a) and 2(b)

However, since the vector $\vec{Q}$ is small, the wave vectors of the graphene dot become periodically multiples of $\vec{q}_h$, and this periodicity manifests itself as a Moiré pattern of the electron density of the graphene quantum dot as Figure 2b shows.

Conclusion. A mechanism for confinement of vortex topologically nontrivial graphene charge carriers in these regions is proposed. It is shown that the stability of atomic-like localized bound Majorana-like states is ensured by their confinement through Majorana resonances emerging in a Klein scattering process.

References

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