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# Electron-photonic topological states on the surface of a bulk semiconductor driven by a high-frequency field

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**Abstract.** It is shown theoretically that the strong coupling of electrons in a bulk gapless semiconductor (HgTe) to a circularly polarized high-frequency electromagnetic field induces topological states on the surface of the semiconductor. Their branches lie near the center of the Brillouin zone and have the Dirac dispersion. Thus, the light-induced topological phase transition in the semiconductor appears. The structure of the found surface states is studied both analytically and numerically in the broad range of their parameters.

## 1. Introduction

The achievements in the laser and microwave techniques have made possible the optical control of condensed matter structures with a high-frequency electromagnetic field, which is based on the Floquet theory of periodically driven quantum systems (Floquet engineering). Therefore, the Floquet engineering of various low-dimensional structures is in focus of attention last years (see, e.g., Refs. [1, 2] and references therein). Among numerous low-dimensional electronic systems, electrons localized near boundaries of condensed matter structures (surface electronic states) bear a special role. The increasing interest devoted to them is caused by the topologically nontrivial nature of the surface states in topological insulators [4, 3, 5, 6] which behave like an insulator in their bulk but have the gapless conducting electronic modes protected by the time-reversal symmetry at their boundaries. Correspondingly, the Floquet engineering of topological surface states is of broad interest since it can serve an effective tool to control their physical properties. In the given paper, we present the theory of optically induced topological electronic states on the surface of bulk gapless semiconductor.

## 2. Model

For definiteness, we consider the surface electronic states which are localized near the surface (001) of bulk mercury telluride (HgTe) and originate from the light-induced mixing of conduction and valence bands near the center of the Brillouin zone. The Hamiltonian describing these bands without an irradiation, $\hat{\mathcal{H}}(\mathbf{k})$, is the conventional Luttinger Hamiltonian with the terms arisen from the bulk inversion asymmetry of the crystal structure [7], where $\mathbf{k}$ is the electron wave vector. Introducing the electron-field interaction within the minimal coupling scheme, the Hamiltonian of irradiated semiconductor, $\hat{\mathcal{H}}(\mathbf{k},t)$, results from the "bare" Hamiltonian, $\hat{\mathcal{H}}(\mathbf{k})$, with the formal replacement $\mathbf{k}\to\mathbf{k}-(e/\hbar)\mathbf{A}(t)$, where $\mathbf{A}=(E/\omega)(\cos\omega t,\,\sin\omega t,\,0)$ is the time-dependent vector potential of the circularly polarized field near the irradiated surface, $E$ is the amplitude of the field, and $\omega$ is the frequency of the field. Solving the non-stationary Schrödinger problem with the time-dependent Hamiltonian, $\hat{\mathcal{H}}(\mathbf{k},t)$, within the Floquet-Magnus approach (see, e.g., Ref. [8]), we can reduce the time-dependent Hamiltonian to the effective time-independent Hamiltonian, $\hat{\mathcal{H}}_{\text{eff}}(\mathbf{k})$, which describes stationary electronic properties renormalized by the irradiation. Considering the stationary Schrödinger problem with the effective Hamiltonian, $\hat{\mathcal{H}}_{\text{eff}}$, we arrive at the renormalized electron energy spectrum and electron wave functions of the semiconductor. It follows from the found solutions of the Schrödinger problem that this light-induced renormalization results in the surface-localized electronic states.

## 3. Results and conclusion

In the particular case of gapless semiconductor with symmetric electron-hole system, the localization length of the found electronic states near the surface, $\lambda$, can be written as

$$1/\lambda=\left|\sqrt{3}\alpha/4\gamma_2\right|-\sqrt{\left(\sqrt{3}\alpha/4\gamma_2\right)^2-\Delta/4\gamma_2}\,,$$

where $\gamma_2$ is the Luttinger parameter of the semiconductor band structure, $\alpha$ is the band parameter corresponding to the Hamiltonian terms linear in $\mathbf{k}$, and $\Delta=2\gamma_2(eE/\hbar\omega)^2$ is the field-induced gap between the conduction and valence bands in the Brillouin zone center. If the irradiation is absent ($E=0$), the surface states vanish ($1/\lambda=0$). Therefore, the discussed surface states exist only in the presence of the irradiation and, thus, are optically induced. As to energy spectrum of these states, $\varepsilon$, it linearly depends on the wave vector, $\mathbf{k}=(k_x,k_y)$, near the Brillouin zone center, $\varepsilon(k_x,k_y)=\pm\sqrt{3}\alpha\sqrt{k_x^2+k_y^2+\sqrt{3}k_xk_y}$, what is the characteristic feature of the topological surface states [4, 3, 5]. It follows from the performed analysis that the optically induced topological states exist only near the Brillouin zone center and merge into the spectrum of bulk conduction band if the plane electron wave vector, $k_{x,y}$, is large enough. It should be stressed that the same circularly polarized irradiation induces the gap between the conduction and valence bands, $\Delta$. Thus, the irradiation turns mercury telluride into topological insulator from gapless semiconductor. As a consequence, the light-induced topological phase transition takes place.

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