Light-induced switch based on edge modes in irradiated thin topological insulators

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Abstract
We investigate transport properties through the nano-ribbons of thin topological insulators irradiated by circularly polarized light in a high-frequency regime. It is demonstrated that pseudo-spin polarized edge modes appearing in the bulk band gap are responsible for the current flowing through this nano-junction whose localization on the top and bottom edges depend strongly on the polarization of light. Based on these edge modes, one can design a light-induced switch with a desirable on/off ratio of the current whose off-state is engineered by dividing the scattering region into two parts. Each part is irradiated by the light with opposite polarization in respect to the other one. This off-state arises from the quantum blocking of transition between two edge modes with opposite pseudo-spin polarization induced by irradiation. The local current on each bond shows how the current passes through the edges and jumps to the opposite edge. Furthermore, some other nano-junctions are proposed as a light-induced switch which are designed based on the gap opening induced by the perpendicular magnetization or structural inversion asymmetry.

1. Introduction
To achieve the best control and performance in electronic devices, considering two-dimensional (2D) materials is necessary and unavoidable. Although many 2D semiconductors have been investigated for this purpose, no one could overcome all challenges in practice. The most important challenge for the new 2D materials is having significant higher mobility in compared to silicon. Although graphene as an intrinsically thin material wins the mobility competition, it has no band gap to be used in the field effect transistors (FETs) and any try to induce a band gap reduces its mobility drastically [1]. On the other hand, sensitivity of the band structure and mobility of electrons to any edge roughness, imperfection and edge passivation decommission graphene nanoribbon as a good candidate for FETs [2]. However, a perpendicular electric field can induce a band gap in bilayer graphene with a high mobility at room temperature [3]. Transition metal dichalcogenides, despite their advantages, have low mobility and high level of defects [4]. Phosphorene and also Silicene have also very low mobility in practice [5]. The first silicene-based FET operating at room temperature has successfully been fabricated which unlike graphene indicates the likely presence of an energy band gap in its electronic structure [6].

Besides all materials used in conventional FETs, topological insulators (TIs) have some other advantages to propose for potential applications in electronic devices [7]. TIs are quantum materials that behave as an insulator in the bulk while depending on their dimension, there are some conducting states on their surface or edges. The surface (edge) states are protected by time-reversal symmetry (TRS) which persist even at a high-level of non-magnetic imperfections such as vacancies, doping and impurities. So electronic devices fabricated based on TIs operate in low power with high performance [7]. Many investigations have been implemented to fabricate FETs from TIs since their discovery [7–9]. Among all approaches for designing a switch in TIs, making
a control on the phase transitions, especially by inducing a gap in the surface (edge) states, is a straightforward way in practice.

In this work, a FET is designed based on the quantum anomalous Hall insulator (QAHI) phase. QAHI phase was initially observed in thin films of \((Bi_2Se_3)\) which were doped by magnetic impurities, such as Cr [16, 11] and V [12]. Materials such as \(Bi_2Te_3\) [13], \(Sb_2Te_3\) [14], \(Bi_2Te_3\) [15] and HgTe [16] have a strong spin–orbit coupling conducting to three-dimensional topological insulators. The gapless surface states with Dirac cone dispersion on their surfaces are the characteristic of such materials. Two Dirac cones overlap with each other in a thin version of the above materials giving rise to an effective 2D TI.

Recent improvements in mid-infrared lasers opened an opportunity for engineering the electronic band structure and also inducing topological phases in trivial materials by irradiating polarized light. Inducing topological phases and even switching between them have been shown to emerge in HgTe quantum wells [17], cold atoms [18, 19], conventional insulators [20–23] and semi-metallic materials [24–29] by application of time-periodic driving fields. Moreover, Floquet-Bloch states [21, 30] have been experimentally observed in topological insulator \(Bi_2Se_3\) illuminated by circularly polarized light [31, 32].

In particular, in high-frequency regime in which the driven frequency is much larger than the band width, one can use an effective static Hamiltonian which is composed of series expansion to the inverse powers of frequency [21, 33]. One of the advantages of the off-resonant regime is the population of Floquet states which are occupied like the equilibrium systems [34]. Furthermore, in the off-resonant regime, heating rate is low which is in favor of an electronic device to operate properly [35].

In this paper, we investigate transport properties of nano-junctions of a thin topological insulator illuminated by circularly polarized light in the off-resonant regime using Landauer formalism. It should be noted that in the high-frequency regime, coherent and quantized transport through the nano-ribbon is guaranteed and then Landauer formalism is applicable. Our aim is to present a light-induced switch whose scattering region is composed of two parts. The off-state of this switch is working based on the quantum blocking of transitions between two opposite pseudo-spin polarized states which are induced by illuminating each part with opposite circularly polarized light in respect to the other part. In this switch, there is no need for the gap opening; however, if the perpendicular magnetization or structural inversion asymmetry (SIA) is applied on the irradiated thin TI, a gap is opened in the surface states leading to the normal insulator phase and consequently to the off-current state of the switch. The details of switching phenomena and also edge currents are clearly explained by the local current distribution through the TI nano-ribbon.

This paper is organized as follows: In section 2, we present the low-energy Hamiltonian of a two-dimensional topological insulator in the dark mode and by the high-frequency expansion [36–38], an effective static Hamiltonian is presented for the driven system. The effective Hamiltonian in the absence and presence of SIA potential is extracted in sections 2.1 and 2.2 respectively [39]. In section 3, based on a tight-binding version of Hamiltonian, Landauer formalism is presented for the calculation of current passing through the nano-ribbon. In section 4, we present the result of I-V characteristic curves and switching phenomena for different cases. Finally, we conclude our findings in section 6.

2. Dark and photo-assisted Hamiltonians

Light–induced switch introduced in this paper is based on two-dimensional topological insulators designed on thin films of \(Bi_2Se_3\) and \((Bi,Sb)_2 Te_3\) family materials [40]. There are two Dirac cones on each surface which can be hybridized if the film is thinner than 5 nm [41, 42]. Tunneling between the upper and lower surfaces leads to a gap opening in the surface states forming inside the bulk band gap such that the system is inverted to a 2D insulator. Interestingly, the topological invariant of the system is changed by using magnetic impurities such as Ti, V, Cr and Fe, and also structural inversion asymmetry, so the edge modes may re-appear inside the gap. It should be noted that irradiation of a polarized light leads to a rich feature of the phase diagram. In the absence of an external magnetic field, under illumination of high-frequency light, by tuning the light parameters such as intensity and polarization along with induced magnetization or structural inversion asymmetry, one can engineer different topological phases such as quantum pseudo-spin Hall insulator or quantum anomalous Hall insulator [38, 39]. The low energy effective Hamiltonian for the dark mode around the \(\Gamma\) point is written [43, 44] as the following:

\[
H_{\text{dark}}(k) = \hbar \omega \tau_z \otimes (k_y \sigma_5 - k_x \sigma_y) + \Delta(k) \tau_x \otimes \sigma_0 + V_{\text{SIA}} \tau_z \otimes \sigma_0 + M z \tau_0 \otimes \sigma_z
\]  

(1)

Without loss of generality, we have neglected particle-hole symmetry term in this Hamiltonian. The basis set in which the above Hamiltonian is written is represented as \(|t, \uparrow\rangle, |t, \downarrow\rangle, |b, \uparrow\rangle, |b, \downarrow\rangle\), where \((t,d)\) refers to the top (bottom) surface states and \(\uparrow(\downarrow)\) displays the up (down) spin state. The matrix \(\tau_i(\sigma_i)\) in Hamiltonian is
Pauli matrix in the surface (spin) space. The surface state as a Dirac cone spectrum with Fermi velocity $v_F$ appears in the first term. The second term comes from the tunneling between these Dirac cones localizing on the surfaces. The tunneling parameters are experimentally fitted in the following k-dependent parameters $\Delta(k) = \Delta_0 + \Delta_1 k^2$ for thin films of Bi$_2$Se$_3$ and [(Bi,Sb)$_2$Te$_3$] family [41, 42]. These parameters depend on the thickness of the TI thin film. The third term is related to the structural inversion asymmetry $V_{SIA}$ which could be generated by using either of two factors: perpendicularly applied electric field or substrate effects [41].

Finally, the last term expresses the effect of induced electric field arising from doped magnetic impurities in Bi$_2$Se$_3$ and [(Bi,Sb)$_2$Te$_3$] family [43]. In this work, we consider system parameters such as $\Delta_0 = 35$ meV, $\Delta_1 = -10$ eVÅ$^2$ and $v_F = 4.48 \times 10^5$ ms$^{-1}$. The driven frequency is chosen to be $\hbar \Omega = 1$ eV which is much larger than the bulk band gap. As we will discuss later in section 6, to avoid transition between the central Floquet side-bands, we should use the light with high frequencies as well as low intensities.

A change in the basis set using a unitary transformation does not change the eigenvalues of the system. Let us write the new basis set by using the bonding and antibonding states as $|\psi_{\alpha}\rangle = \langle \alpha | \psi \rangle$. Now one can derive the new form of Hamiltonianin in the basis of $|\psi_{\alpha}\rangle$:

$$H'_\text{dark}(k) = h v_F (k_x \gamma_0 \sigma_x + k_y \gamma_1 \sigma_y) + (\Delta(k) \gamma_0 + M_z \sigma_z) \sigma_z + V_{SIA} \gamma_1 \sigma_z \gamma_1$$

(2)

in which $\gamma_i$ and $\gamma_2$ ($i = 0, x, y, z$) are Pauli matrices in the bonding and anti-bonding and also spin Hilbert space.

### 2.1. Perpendicular magnetization at zero SIA potential

In this new form of Hamiltonian, it is clear that if $V_{SIA} = 0$, the above effective Hamiltonian 2 would be blocked with the diagonal matrices labeled by the pseudo-spin index ($\alpha = \pm$) as the following [45–47]

$$h'_{\text{dark}}(k) = \hbar v_F (k_x \sigma_x + \alpha k_y \sigma_y) + (\Delta(k) + \alpha M_z) \sigma_z$$

(3)

Illumination of light with circular polarization on a TI thin film is simulated by the following time-periodic vector potential: $A(t) = A_0 \sin(\Omega t)$, $\cos(\Omega t)$ where $[\Omega] = 2\pi / T$ is the frequency of the drive. The sign of $\Omega$ refers to the left or right-handed polarization. Thanks to the Peierls substitution which is a change in the wave vector induced by the vector potential as the following: $k_1 \rightarrow k_1 + \frac{\hbar \Omega}{v_F}$. It is straightforward to substitute this wave vector in Hamiltonian 1 giving rise to a time-periodic Hamiltonian. This type of Hamiltonian is studied using Floquet theory [21]. In this theory, one can define a Floquet Hamiltonian which describes system evolution in stroboscopic times (multiplier of $T$). The Floquet-Schroedinger equation is represented as

$$\left[ H_F(t) - i \hbar \frac{\partial}{\partial t} \right] \phi_\alpha(t) = \varepsilon_\alpha \phi_\alpha(t)$$

(4)

where $\phi_\alpha(t)$ is the Floquet state which obeys the periodicity of the vector potential as well as $H(t)$. Here, the quasi-energy of this Hamiltonian, $\varepsilon_\alpha$, is formed in a band spectrum which contains central Floquet bands and also infinite side-bands. The Fourier transformation of the above equation is simply inverted to the following eigenvalue equation;

$$\varepsilon_\alpha + m \hbar \Omega |\phi^{(m)}_\alpha\rangle = \sum_{m'} H_F^{(m-m')} |\phi^{(m')}_{\alpha}\rangle$$

(5)

where Fourier coefficient of the Floquet Hamiltonian is defined as $H_F^{(m)} = 1/T \int_0^T H_F(t) e^{im\Omega t} dt$. Fortunately at low intensity of irradiations, if the energy of the incident photons is higher than any characteristic energy of the system (here the bulk band gap), it is straightforward to find a series expansion for the Floquet Hamiltonian in terms of the inverse frequency $1/\Omega$ formed as the following photon-dressed Hamiltonian [36, 37, 48],

$$H_{\text{eff}} = H_F^{(0)} + (\hbar \Omega)^{-1} [H_F^{(1)}, H_F^{(1)}] + O \left( \frac{1}{(\hbar \Omega)^2} \right)$$

(6)

where it is proved that $H_F^{(i)} = 0$ (for $i = 0, \pm 1$). Looking at the above effective Hamiltonian deduces that the one-photon process is only assisted in transmission phenomena. Let us look at the effective Floquet Hamiltonian if $V_{SIA} = 0$. In this case, as we mentioned before, the dark Hamiltonian is pseudo-spin polarized even if perpendicular magnetization is applied on the film. After Peierls substitution in the dark pseudo-spin polarized Hamiltonian, one can simply drive the effective Hamiltonian as

$$h_\alpha = \hbar v_F (k_x \sigma_z - \alpha k_y \sigma_y) + [\Delta'(k) + \alpha (M_z + m_0)] \sigma_z$$

(7)
where

\[
\Delta'(k) = \Delta_0 + A^2 \Delta_1 + k^2 \Delta_2, \quad A' = \frac{A^2}{\hbar \Omega}
\]

\[
\eta_\sigma = 1 - 2 \alpha A' \Delta_1, \quad m_{\Omega} = \hbar^2 v_f^2 A'
\]  \hspace{1cm} (8)

In this formula, the scaled intensity is defined as \( A = e A_0 / \hbar \). Regarding the sign of the mass term, the pseudo-spin Chern number is given by \( \zeta_0 = \alpha / 2 (\text{sgn}(\Delta_0) - \text{sgn}(\Delta_0 + A^2 \Delta_1 + \alpha m)) \) where \( \text{sgn} \) refers to the sign function and \( m = M_x + m_0 \) in which \( m_0 \) plays the role of the mass term induced by the illuminated light. The total Chern number is written as \( C = C_++C_- \). The phase diagram of this Hamiltonian has been investigated in [38] in detail. Depending on the sign of \( \Delta_0 \times \Delta_1 \) and the value of light parameters such as the intensity, polarization of light and also system parameters such as magnetization \( M_z \) in the phases such as quantum anomalous Hall insulator, normal insulator, and quantum pseudo-spin Hall insulator are achievable [38]. The other interesting phenomenon is anisotropic helical edge states appearing in the coefficient \( \eta_\sigma \). In fact, the Fermi velocity can be different for each pseudo-spin such that the difference depends on the light intensity, frequency and also hopping parameters between two surfaces. In all calculations in which the light is turned on, the scaled vector potential is considered to be \( A' = 0.5 \text{ nm}^{-2} \).

2.2. In presence of SIA potential

In the presence of SIA potential, the Hamiltonian (2) can not be diagonalized on the pseudo-spin basis set and consequently, the edge states in topological phases are a mixture of these two pseudo-spin polarized states [49]. Therefore, we begin with the dark Hamiltonian itself indicated in equation (1). After Peierls substitution and in the high-frequency regime and low intensity of the driven fields, the following Hamiltonian is deduced,

\[
H = (1 - 2 A' \Delta_1 \tau_z) / h v_f (k_x \sigma_x - k_y \sigma_y) + [\Delta'(k) + \tau_z m] \sigma_z + V_{SIA} \tau_x \sigma_x
\]  \hspace{1cm} (9)

The gap-closing conditions for the above Hamiltonian demonstrate that after a critical SIA potential there would be phase transitions from QAHI and also QPHI to NI depending on the initial phase at zero SIA potential. A detailed study is found in [39].

3. Tight-binding and Landauer formalism

To investigate transport properties of the edge modes of topological insulators by using Landauer formalism, it is convenient to cut the film into a nano-ribbon shape. To do this, let us discretize the Hamiltonian presented in equation (2) on a square lattice,

\[
H = \sum_\mathbf{r} \left[ c_{\mathbf{r}}^\dagger T_0 c_\mathbf{r} + c_{\mathbf{r}+\hat{x}}^\dagger T_x c_\mathbf{r} + c_{\mathbf{r}+\hat{y}}^\dagger T_y c_\mathbf{r} + h.c. \right]
\]  \hspace{1cm} (10)

where \( c_{\mathbf{r}}^\dagger \) and \( c_\mathbf{r} \) are the creation and annihilation operators defined on the site \( \mathbf{r} \), and

\[
T_0 = \begin{pmatrix}
\Delta_0' + \frac{4 \Delta_1}{a^2} & \gamma_0 \sigma_z + m \gamma_z \sigma_z + V_{SIA} \gamma_x \sigma_x \\
\gamma_0 \sigma_z + m \gamma_z \sigma_z + V_{SIA} \gamma_x \sigma_x & \Delta_0' - \frac{4 \Delta_1}{a^2}
\end{pmatrix}
\]

\[
T_x = - \frac{\Delta_1}{a^2} \gamma_0 \sigma_z + \frac{h v_f}{2 a} (\gamma_x \sigma_y - 2 A' \Delta_1 \gamma_0 \sigma_y)
\]

\[
T_y = - \frac{\Delta_1}{a^2} \gamma_0 \sigma_z - \frac{h v_f}{2 a} (\gamma_0 \sigma_x - 2 A' \Delta_1 \gamma_x \sigma_x)
\]  \hspace{1cm} (11)

in which \((T_0)\) is a 2 \( \times \) 2 onsite-energy matrix and \((T_x, T_y)\) are the hopping-energy matrices along the \( x \) and \( y \) directions, respectively. Here, \( \alpha_\sigma \) is the pseudo-spin index, and \( y = ja \) is the site position along the \( \hat{y} \) direction. The current flowing through the scattering region can be expressed by Landauer formula presented as the following:

\[
I(V_{SD}) = \frac{e}{h} \int_{\mu_L}^{\mu_R} T(E, V_{SD}) (f(E - \mu_L) - f(E - \mu_R)) dE
\]  \hspace{1cm} (12)

Where \( f(E, E_f) \) is the Fermi–Dirac distribution function and \( \mu_L (\mu_R) \) is the chemical potential of the left (right) electrode. \( T(E, V_{SD}) \) is the transmission coefficient which is obtained by \( T = \text{Tr} [\Gamma_L G_C \Gamma_R G_C^\dagger] \), where \( G_C (G_C^\dagger) \) is the retarded (advanced) Green’s function of the scattering region and \( \Gamma_L (\Gamma_R) \) is the coupling function of the scattering region with the left (right) electrode.

In the presence of the source–drain bias, the local charge current from the site position \( \mathbf{r} \) toward the other site \( \mathbf{r} + \mathbf{r}_0 \) is calculated by:
Two helical edge modes which are pseudo-spin polarized are shown by the blue (pseudo-spin +) and purple (pseudo-spin −) arrows. (a2) band structure of the dark nano-junction in which black bands indicate the degeneracy of two pseudo-spin polarized bands. (b1) and (c1) the system is illuminated by (RCP and LCP) light so that a phase transition from QPHI to QAH phase occurs. In low energies, depending on the polarization of light, only one pseudo-spin polarized edge mode (+ or −) is hosted which is shown by the (blue and purple) arrows respectively. (b2) and (c2) band structure of a thin topological insulator illuminated by (RCP (LCP)) light in which blue (purple) bands show pseudo-spin + (−) states. (a3), (b3), (c3) Current distribution of the scattering region sandwiched between two dark electrodes under the application of source-drain potential confirms proposed distributions based on topological phases in each case. (d3) Conductance of the nano-junction composed of a four-step mass-term structure made by topological insulator nano-ribbons irradiated by LCP (left portion) and RCP (right portion) light. (d1), (d2) band structure of the left and right portion of this four-step mass-term structure.

\[
J_{\text{r,f}+\tau_0} = \frac{e}{h} \int_{-\infty}^{\infty} dE [H_{\text{r,f}+\tau_0} G^r_{\text{r,f}+\tau_0} (E) - H_{\text{r,f}+\tau_0} G^r_{\text{r,f}+\tau_0} (E)]
\]

in which the lesser Green’s function is calculated by the Keldysh equation [50].

\[
G^< (E) = G^r (E) \Sigma^< G^a
\]

where the lesser self-energy is defined in terms of the left and right self-energies induced by the electrodes,

\[
\Sigma^< = \sum_{L(R)} i \tilde{\rho} (E) \tilde{V}_{L(R)} (E).
\]
4. Results

Before turning on the irradiation, firstly let us investigate switching phenomena in the absence of SIA potential and also in the lack of magnetic impurities. Regarding the phase diagram shown in figure 5 with a choice of $\Delta_0 \Delta_1 < 0$, all three portions of the nano-junction are in the QPHI phase [38]. In low energies, two pseudo-spin polarized edge states are flowing through the nano-junction helically. As it was noted before in equation (7), depending on the light intensity and frequency of the pump, anisotropic helical states essentially emerge which have different Fermi velocities. However, by our considered parameters, this difference is too small to affect the band spectrum and also transport phenomenon.

A schematic view of the dark nano-junction is drawn in figure 1(a1) which shows the + (blue) and − (purple) pseudo-spin polarized edge currents. Moreover, the band spectrum of this nano-ribbon confirms the emergence of these degenerated pseudo-spin polarized edge modes inside the band gap. This phase corresponds to the QPHI phase referring to the origin in the phase diagram drawn in figure 5 with $M_2 = \mathcal{A} = 0$. It is worth to note that the states localized on the edges decay exponentially in the bulk region with a penetration depth which is inversely proportional to the band gap. To avoid hybridization of the edge states, the nano-ribbon width is considered to be much wider than the penetration depth.

In this stage, the scattering region is irradiated by the left and right-handed circularly polarized (LCP and RCP) light as shown in figures 1(b1), (c1). So the mass-term is varying and the topological phase of the system changes to QAHI. As shown in figures 1(b1) and (c1), the polarization of light opens a selectivity for choosing a special kind of pseudo-spin edge mode to flow through the nano-ribbon. These phases are also indicated in the phase diagram of figure 5 as two points located along the vertical axis ($M_2 = 0$).

By applying a source-drain bias, one of the edge currents is intensified along the transport direction, while the edge current flowing through the opposite direction is removed. In this work, the right electrode operates as the source electrode. Current distributions which are calculated by Landauer formalism are shown in figures 1(a3), (b3), (c3). These current distributions confirm the existence of the edge current as well as their helical property. In a QPHI phase or in the case of dark nano-ribbon, figure 1(a1), because of source-drain external bias, those pseudo-spin states which are allowed to pass along the transport direction contribute helically in the current.

At zero SIA potential and also zero in-plane magnetization, Hamiltonian of equation (7) is pseudo-spin polarized. By using this property, a pseudo-spin selective tunneling occurs at a four-mass-term step nano-junction composed of two regions which are separately illuminated by RCP and LCP light. It is simply verified that in this case, because of the alignment of the edge modes with opposite pseudo-spin states, a transport gap emerges in this nano-junction. Indeed, the transition between these polarized states is forbidden. Figures 1d shows the band spectrum of two regions illuminated by RCP and LCP light and its resultant conductance through the nano-junction which is calculated by non-equilibrium Green’s function formalism.

By taking this significant selective rule, a four mass-term heterostructure is designed on thin topological insulator as a switch induced by the light polarization. In the dark mode (QPHI phase), as far as source-drain bias is applied, the + (−) pseudo-spin edge mode flows through the transport direction from the down (up) edge as shown schematically in figure 2(a1). This analysis is verified by calculating the current distribution represented in figure 2(a2) which is done using non-equilibrium Green’s function formalism. The current is concentrated on the edges of the nano-ribbon which is consistent with the schematic drawing in figure 2(a1).

Now let us depart from the scattering region in two portions which are illuminated separately. First, as shown in figure 2(b1), the right portion is illuminated by the RCP light while the left portion remains in the dark mode. Because of the voltage gradient, both pseudo-spin polarized states are initially contributed in the edge currents inside the source electrode; however, once the RCP light is illuminated on the right portion, the only pseudo-spin which is allowed to tunnel through the right portion would be $\alpha_z = +1$ which flows through the lower edge, so the pseudo-spin states with $\alpha_z = -1$ are filtered by the light illumination. Moreover, the current at the upper edge is blocked, so the polarization of circularly polarized light enables one to select on which edge the current is permitted to flow. By using NEGF calculations, the current distribution depicted in figure 2(b2) confirms what we have proposed in figure 2(b1). At the lower edge inside the source electrode, the edge current is nearly nullified that is explained by that edge current which is reflected from the portion illuminated by the RCP light.

The same phenomenon happens provided that the left portion is illuminated by the LCP light and as what is seen in figures 2(c1) and (c2), the right portion is in the dark mode. In this turn, just the pseudo-spin $\alpha_z = -1$ is permitted to flow through the upper edge. Again, the polarization of light gives the freedom to select the location of the edge current and enables one to use this device as a current splitter. The states with the pseudo-spin $\alpha_z = +1$ are reflected from the junction created between the dark and illuminated regions. Because of the
superposition of these reflected pseudo-spin states with those states with opposite polarization, local current distribution in the right-top edge of the nano-ribbon shows very low current values.

Finally, in figures 2(d1) and (d2), we checked the situation in which both the left and right portions are illuminated by the LCP and RCP light, respectively. As a result, no current passes through the nano-junction and this electronic switch lies in its off-current mode. Note that the local current distribution in the right portion of this nano-junction originates only from \( \alpha_z = +1 \) states which are reflected from the junction between two illuminated regions. Most of the current distribution is concentrated on the right portion which is irradiated by the RCP light. If one looks at the edge currents inside the source electrode (the right side), the helical states with opposite pseudo-spins flow in the opposite directions at each edge, and the superposition of them gives rise to low values of the current.

The current-voltage characteristic curves for all the above cases of the four mass-term heterostructure are summarized in figure 2(e). The I-V curve shows an Ohmic behavior in three different types. The current intensity at a fixed external bias and in the dark mode is twice the current intensity measured in those configurations in which just one portion is illuminated by the polarized light, as depicted in figures 2(b), (c). In the off-state shown in figure 2(e) with the black solid line, the output current is nullified as far as the voltage window of the external bias is smaller than the bulk gap. The Fermi energy is fixed at the zero energy. The on/off ratio of the current at the bias voltage \( V = 10 \text{ mV} \) is of order \( 10^2 \).

In this stage, we investigate the current passing through the nano-ribbon in the presence of perpendicular magnetization or applied electric field in combination with the irradiation. In this case, the off-state occurs when a gap is induced in the surface states and consequently the edge states as a result of irradiation in the presence of mentioned parameters. First of all, we need to review different phases emerging for various parameter values. For the sake of completeness, we refer the reader to the phase diagrams drawn in figures 5, 6 in which the specific points \( \alpha_1, ..., \alpha_4 \) or \( \beta_1, ..., \beta_4 \) are marked, respectively.

As an example, in a switch represented in figure 3, the mass-term of the scattering region is controlled by a combination of the light parameters and magnetization. As seen in the phase diagram shown in figure 5, in the dark mode (\( \alpha_1 \) and \( \alpha_3 \)), there are two QAHI phases with different chern numbers and consequently different edge channels for transport which are induced by the magnetic doping. If the downward magnetization changes to the upward direction, the location of the chiral-polarized edge mode hops from the top to the bottom edge of the nano-ribbon. All these phases can be applied in the TI nano-junction. As shown in figure 3, the scattering region indicated in the panels a1 and c1 is doped by magnetic impurities with opposite magnetization in respect to each other. As it is clearly observed in figures 3(a2), (c2), looking at the local current distribution which is calculated by NEGF formalism demonstrates the localization of the edge transport channels in the top and bottom edges of the nano-ribbon.

Irradiating of the circularly polarized light on the TI nano-ribbon which is doped by magnetic impurities, induces a phase transition from QAHI to NI phase. The points marked by \( \alpha_2 \) and \( \alpha_4 \) in figure 5 are inside the NI
phase induced by the right and left-handed circularly polarized light, respectively. Emerging normal insulator phase can be used for designing an off-state for the electronic switch so that not only there are no bulk transport channels, but the edge modes also disappear. The off-state arising from the gap opening in the edge states is similar to what happens in Esaki diodes. These phase points are simulated in the nano-ribbon shown in figures 3(b1) and (d1) giving rise to the off-state. The local current distribution drawn in figures 3 b2 and d2 demonstrate that for nano-ribbons longer than a tunneling length, no current can pass through the nano-junction.

The current-voltage characteristic curves for all the above cases of the mass-term step junctions are summarized in figure 3(e). The I-V curve shows an Ohmic behavior in two different types in which the slope of the red line is unit representing the contribution of only one edge in transport as depicted in figures 3(a), (c). The off-state of the I-V curve is plotted with the black solid line as shown in figure 3(e).

For the sake of completeness, we investigated the simultaneous effect of SIA potential induced by perpendicular electric field and also the illumination of the circularly polarized light. Interestingly, as shown in figure 6, the topological phase is the QPHI phase for the SIA potentials smaller than a critical value in the dark mode. However, as shown in [39], as a result of applying SIA potential, the Hamiltonian 1 is not broken into pseudo-spin polarized parts and as a consequence, there is a mixture of pseudo-spin states contributing in transport through the edge channels. It is demonstrated that as long as the gap of pseudo-spin operator is opened [39], the pseudo-spin Chern number is still definable and the edge states are revived inside the band gap. However, there is no pseudo-spin polarized edge state in the TI nano-ribbon anymore. Indeed, QPHI phase guarantees the existence of the edge current at both edges of the nano-ribbon, but in this turn, there is a mixture of pseudo-spins flowing through each edge.

Now let us consider three special points in the phase diagram represented in figure 6, \( \beta_1 \) in QPHI phase, and \( \beta_2, \beta_3 \) in NI phases. In the dark mode, under application of SIA potential, the parameters attributed to the phase point \( \beta_1 \) guarantee the existence of non-polarized edge states along the edge channels. The other phase points marked as \( \beta_2, \beta_3 \) are used for the off-state of the switch. To realize the point \( \beta_1 \) in experiment, we suppose a perpendicular electric field applied only on the scattering region of the nano-ribbon in the absence of magnetic doping and also light illumination. As a result, as sketched in figure 4(a1), edge currents containing a mixture of pseudo-spins are flowing through each edge. The local currents of the mixed states are marked by the black arrows. This proposed schematic view is easily confirmed by the current distribution in figure 4(a2). Due to the lack of SIA potential applied on both electrodes, the input and output edge currents are pseudo-spin polarized. As a result, the I-V curve shows an Ohmic law in figure 4(d) (the blue line).

By turning on the circularly polarized light in the scattering region, a phase transition from QPHI to NI occurs and a gap is opened in the non-pseudo-spin polarized edge modes. As is observed in the schematic view of figures 4(b1) and (c1), the pseudo-spin polarized currents are reflected toward the source electrode and no current is passing through the nano-ribbon. It is equivalent to the off-state of the switch. Looking at the local current distributions in figures 4(b2) and (c2) demonstrates a pattern of quantum oscillation for the tunneling
current through the bulk region of the nano-ribbon. The black line in the I-V curve of figure 4(d) represents the off-state of the switch. In conclusion, we propose an electronic switching with off or on-operation by turning on or off the circularly polarized light, respectively.

5. Discussion

The Floquet Hamiltonian of equation (6) is the Van-Vleck expansion in terms of \( A_i / \Omega \). It means that for using this expansion, it is reasonable to decrease the light intensity along with increasing the light frequency [31]. In the high-frequency regime, the central Floquet band is far enough to touch the other side-bands in the dynamical gaps. Besides, the low intensity of light causes a drop in the transition rate from the central Floquet band to the other side-bands giving rise to the localization of the Floquet eigen-states mostly on the central Floquet band.

On the other hand, regarding the realization of such devices in experiment, irradiation of a solid by the light with high frequency and low intensity causes suppression of the heating rate as well. If the energy of photon is larger than any energy change arising from single scattering events in the system, then energy absorption and consequently the heating rate would be exponentially suppressed in \( \omega [35] \).

In our study, we considered the scaled vector potential for all calculations to be \( A_i = 0.5 \text{ nm}^{-2} \), then the amplitude of the electric field is \( E_0 = \frac{\Delta \Omega}{\alpha} = 8.707 \times 10^{-7} \text{ nm}^{-2} \alpha \omega = 0.707 \text{ eV nm} \) which is a reasonable amplitude. The light intensity is estimated to be \( I = 6.7 \times 10^8 \text{ MW cm}^{-2} \).

As checked in [31], the results of the first principle calculations show that the gap opened in the surface spectrum of a 3D Topological insulator illuminated by circularly polarized light has the same values for both the low and high-frequency regimes (\( \hbar \Omega = 0.2, 5 \text{ eV lower and higher than the bulk gap} \)). The reason stems from the role of intensity that for illuminating light with lower frequency, we should also use lower intensity for the light to preserve the condition of the off-resonant regime in the Van-Vleck expansion.

It should be noted that in this study, the critical light intensity required for switching depends on the mechanism through which the current is set off. If parameters such as \( M_i \) and \( V_{ix} \) are zero, regarding to figures 5, 6, it is enough to consider the light intensity as large as \( A_i = 0.2 \text{ nm}^{-2} \) to make sure there is a phase transition from QPHI to QAH phase. By application of \( M_i \) or \( V_{ix} \), a gap is opened in the surface states and the minimum light intensity required for switching will be extracted from figures 5, 6 such that the phase transition from QAH to NI is guaranteed.

Interestingly, another dependent parameter for controlling the band gap and consequently the minimum intensity required for the phase transition is the hopping parameters between two surface Dirac cones (which are experimentally fitted to \( \Delta_0 \) and \( \Delta_1 \)). These parameters affect the phase diagram boundaries (Please refer to [[39], figure 5]). As shown in the mentioned reference, if the hopping parameter \( \Delta_0 \) (and so the band gap) decreases from 35 meV to 5 meV, the minimum intensity required for a phase transition (the points marked by \( \alpha_3 \) and \( \alpha_4 \)) decreases one order of magnitude (\( I' = 0.1I \)).
6. Conclusion

An electronic switch is designed by irradiating the circularly polarized light on a thin topological insulator realizing in the thin films of Bi$_2$Se$_3$ and [(Bi,Sb)$_2$Te$_3$] family in the high-frequency regime. The characteristic I-V curve of a nano-ribbon of TI thin film connected to two dark electrodes is studied using non-equilibrium Green’s function formalism. In the scattering region, by an illumination of the circularly polarized light, or a change in perpendicular magnetization or also an applied potential, one can control the mass-term of the system and design a switch. Thanks to the pseudo-spin polarized Hamiltonian in the absence of SIA potential and also magnetization, we presented the first proposition for designing a switch based on the edge current through the TI’s nano-ribbon. In this case, the scattering region is departed into two portions, each part is selectively shined by the LCP or RCP light. The polarization of light gives the possibility of determining on which edge the current is demanding to pass. The off-state of the current arises from the quantum blocking of transitions between two modes with opposite pseudo-spin polarization. The modes with opposite pseudo-spin polarization are provided by illuminating opposite circularly polarized light on each part, simultaneously.

In the second set-up, by applying $M_z$, the nano-ribbon is set in the QAHI phase giving rise to the edge current. By turning on the LCP or RCP light, a gap is opened in the edge states and consequently, the current flowing through the edges is cut off. Finally, the last version of the switch is operating by application of a perpendicular potential which leads to the QPHI phase. The edge current, in this case, is again cut off by illuminating the LCP or RCP light giving rise to opening a gap.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Appendix A. Phase diagrams

Two decoupled pseudospin Hamiltonians given by equation (7) in the absence of SIA, show several topological phases depending on the experimentally tuning parameters. In both the absence and presence of magnetic impurities, one can tune $\Omega$ and modify the topological phases by changing the intensity, frequency, and polarization of light.

By taking $M_z$, the solid lines in the phase diagram of figure 5 arising from $m_{t1} = - M_z + \Delta'_0$ [38], divide the $M_z - \Delta_0^2$ phase space into several distinct topological phases denoted; by the gray region as QPHI (−1, 1) composed of two edge states with fully pseudo-spin polarization ($\alpha_z = -1$ and $\alpha_z = +1$), the blue region as QAHI (−1, 0) composed of one edge state with fully pseudo-spin polarization ($\alpha_z = +1$) and finally the yellow regions as NI (0, 0) which are fully

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**Figure 5.** Phase diagram of a magnetically doped thin topological insulator which is irradiated by circularly polarized light. Four distinct phases with specific pseudo-spin Chern numbers (C+, C−) as QPHI (−1, 1), QAHI (−1, 0), QAHI (0, 1), NI (0, 0) are achievable by different amounts of magnetization and light intensity.
gaped without any edge states. Here the points $\alpha$ corresponds to the parameters of different configurations of figure 3.

As mentioned before, the Hamiltonian does not commute with the pseudo-spin operator $\tau_z$. Although the pseudo-spin Chern number is still definable, the quantum number $\alpha_z$ is not invariant as far as $\text{VSIA} \neq 0$. Taking $\text{VSIA}$ induced by the electric field, in this turn, the gap closing occurs at the $\Gamma$ point $(k = 0)$ and $k^2 = -\frac{\Delta_0}{2\Delta} - 2A'm > 0$ with the phase boundaries; the solid lines in the phase diagram of figure 6 are obtained if

$$V_{\text{SIA}}^2 = m^2 - \Delta_0^2$$

in which $m = m_2 + m_1$ and the dash lines are derived if [39].

$$V_{\text{SIA}}^2 = \frac{(-1 + 4A'^2\Delta_1^2)}{\Delta_1}(-m^2\Delta_1 + \hbar^2v_f^2(\Delta_1' + 2A'm\Delta_1))$$

Now there are still four distinct topological phases in the $V_{\text{SIA}} - A'$ phase space which are depicted by QPHI ($-1, 1$), QAHI ($-1, 0$), QAHI (0, 1) and NI (0, 0).

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**Figure 6.** Phase diagram of a thin topological insulator irradiated by circularly polarized light and applied perpendicular electric field simultaneously. Four distinct phases with specific pseudo-spin Chern numbers $(C^+, C^-)$ as QPHI ($-1, 1$), QAHI ($-1, 0$), QAHI (0, 1), NI (0, 0) are achievable by different amounts of $V_{\text{SIA}}$ induced by the electric field and light intensity. Solid (dashed) curves are related to the gap closing at (out of) the $\Gamma$ point.
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