Valley-Controlled Transport in an Optically Driven Biased Dice Lattice

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Abstract. We study the valley-controlled transport in a symmetrically biased dice lattice in the presence of an off-resonant circularly polarized light. We find that the interplay between the bias term and the off-resonant induced mass term leads to a different band gaps in $K$ and $K'$ valleys. The valley Hall conductivity is calculated as a function of the chemical potential for different values of mass terms. It is demonstrated that due to the off-resonant light, 100% valley polarized transport can be achieved.

INTRODUCTION

Two-dimensional crystals with honeycomb lattice structures such as graphene [1], silicene[2] etc host quasi-particles which possess the valley degree of freedom in addition to their charge and spin. This additional degree of freedom is associated with the existence of two inequivalent valleys, namely $K$ and $K'$, in the Brillouin zone. A new research field known as “valleytronics” has been developed in recent years aiming to detect the valley current[3-5] which has potential application for quantum information processing. In order to explore the valley-contrasting physics such as the Valley Hall effect, the inversion symmetry of the underlying physical system must be broken which, therefore, enables a gap in the low energy spectrum. Some inversion symmetry broken systems often exhibits energy gaps of equal magnitude in both valleys. The valley polarization in such system, however, is not possible to obtain in equilibrium. To achieve 100% valley polarization, the gap in one valley needs to be closed. This gap closing in one valley may be realized dynamically by means of a monochromatic circularly polarized light which enable us to tune the valley-contrasting phenomena externally. In this work, we investigate valley-controlled transport properties of a symmetrically biased dice lattice under off-resonant circularly polarized light. A dice lattice has a honeycomb lattice structure with an additional atom located at the centre of each hexagon. It can be engineered in a tri-layer structure of a cubic lattices, namely, SrTiO$_3$/SrIrO$_3$/SrTiO$_3$ grown in (111)-direction [6]. The low energy excitations in a dice lattice are described by the Dirac-Weyl Hamiltonian with pseudo-spin $S = 1$. In a symmetrically biased dice lattice, the bias term explicitly breaks the inversion symmetry. The effect of an off-resonant circularly polarized light is to provide a valley dependent mass term which breaks the time-reversal symmetry. The valley dependent mass term can be tuned by changing the polarisation and the frequency of the off-resonant light. Therefore, the interplay of two mass terms, the bias term and the valley dependent mass term has the potential to control the valley dependent transport in a system.
Model and Methods

In the low energy approximation, the tight binding Hamiltonian corresponding to a symmetrically biased dice lattice in momentum space can be written as [7],

\[ H_0(k) = \begin{pmatrix} \delta & \frac{g_k}{\sqrt{2}} & 0 \\ \frac{g^*_k}{\sqrt{2}} & 0 & \frac{g_k}{\sqrt{2}} \\ 0 & \frac{g^*_k}{\sqrt{2}} & -\delta \end{pmatrix}, \tag{1} \]

where \( g_k = \hbar v_F (\eta k_x - k_y) \) with \( v_F \) as the Fermi velocity and \( \eta = \pm 1 \) is the valley index. The bias \( \delta \) essentially breaks the inversion symmetry to open a gap in the energy spectrum. Now the system is exposed to a circularly polarized off-resonant light. The light in the off-resonant condition is unable to excite electrons from the valence band to the conduction band, however, it renormalizes the band structure significantly via virtual photon emission/absorption process. This condition satisfies when \( \hbar \omega \gg t \), where \( \omega \) is the frequency of the light and \( t \) is hopping parameter. The off-resonant light is described by the vector potential \( \vec{A}(t) = E_0 \omega (\cos \omega t, \gamma \sin \omega t) \), where \( E_0 \) is the amplitude of the electric field of the radiation and \( \gamma = \pm 1 \) represents the right (left) circularly polarized light. The Hamiltonian given in Eq. (1) becomes time periodic with period \( T = \frac{2\pi}{\omega} \) which allows one to use the Floquet theory. Within the framework of the Floquet theory [8], an effective time-independent Hamiltonian in the off-resonant regime is obtained as

\[ H_{\text{eff}}(k) = \begin{pmatrix} \Delta_\eta & \frac{g_k}{\sqrt{2}} & 0 \\ \frac{g^*_k}{\sqrt{2}} & 0 & \frac{g_k}{\sqrt{2}} \\ 0 & \frac{g^*_k}{\sqrt{2}} & -\Delta_\eta \end{pmatrix}, \tag{2} \]

where \( \Delta_\eta = \left( \delta + \frac{\Delta_\omega}{2} \right) \) with \( \Delta_\omega = \frac{\gamma \eta e^2 E_0^2 v_F^2}{\hbar \omega^3} \) is the mass term induced by the off-resonant light. It breaks the time-reversal symmetry and has opposite signs in the two valleys. The effective Hamiltonian is diagonalized to obtain the energy eigenvalues as

\[ E_0(k) = 0, E_\pm(k) = \pm \sqrt{\varepsilon_k^2 + \Delta_\eta^2}, \tag{3} \]

where \( \varepsilon_k = \hbar v_F k \). Note that an off-resonant light is unable to alter the properties of the flat band \( E_0(k) \). However, it is responsible to inducea valley-dependent energy gap \( 2|\Delta_\eta| \) between the conduction band \( E_+(k) \) and the valence band \( E_-(k) \). This gap can be tuned by changing the polarisation and the amplitude of the off-resonant light through the gap tuning parameter \( \Delta_\omega \).

To explore the valley-controlled transport properties of a driven dice lattice, we mainly intend to calculate the valley Hall conductivity. The expression for the anomalous Hall conductivity is given by [9]

\[ \sigma_{xy}^\eta = \frac{e^2}{h} \int \frac{d^2k}{(2\pi)^2} \sum_m f_m(k) \Omega_m(k), \tag{4} \]
where $f_m(k)$ denotes the Fermi-Dirac distribution function and $\Omega_m(k)$ is the Berry curvature of $m$th energy band. The valley Hall conductivity is defined as $\sigma_{xy}^v = \sigma_{xy}^K - \sigma_{xy}^{K'}$. For an irradiated dice lattice, we obtain the Berry curvature for individual bands as

$$\Omega_0(k) = 0 \text{ and } \Omega_\pm(k) = \mp \eta \frac{\Delta_\eta}{(\varepsilon_0^2 + \Delta_\eta^2)^{3/2}}. \quad (5)$$

**RESULTS AND DISCUSSIONS**

The quasi-energy band structure of a symmetrically biased dice lattice driven by a right-circularly polarized off-resonant light is depicted in Fig. 1. It is obtained that the external light enhances the band gap in the $K$ valley and reduces it in the $K'$ valley. More specifically, when the condition $\Delta_\omega = 2\delta$ is satisfied one obtains a gapless Dirac cone in the $K'$ valley. This scenario is shown in Fig. 1 by considering $\delta = 30$ meV. In this particular case, only one valley is relevant for device applications, enabling almost 100% valley polarization.

![Image of quasi-energy band structure](image1)

**FIGURE 1:** The quasienergy band structure of an irradiated dice lattice for (i) $K$ valley and (ii) $K'$ valley

The variation of the valley Hall conductivity with the chemical potential for different values of $\Delta_\omega$ at $T = 10$ K is shown in Fig. 2. We observe that for $\Delta_\omega \neq \delta$, both the valleys contribute to the valley Hall conductivity in a different way, however only one valley contributes in the case of $\Delta_\omega = 2\delta$.

![Image of valley Hall conductivity](image2)

**FIGURE 2.** Variation of the Valley Hall conductivity with the chemical potential for different values of $\delta$ and $\Delta_\omega$.
CONCLUSIONS
In this work, we investigate the valley-controlled transport properties of a biased dice lattice driven by an off-resonant light. We find that the off-resonant light helps to achieve almost 100% valley polarization by making one of the Dirac cones gapless. This also reflects in the behaviour of the valley Hall effect.

REFERENCES