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The effect of X-ray irradiation on conductivity of *C* and *2C* polytypes TiInS_2 ferroelectrics

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The influence of X-ray irradiation on DC conductivity of TiInS_2 *C* and *2C* polytypes are studied in temperature range of 100 – 300 K. The X-ray irradiation (absorbed doses are 0.9 kGy and 2.7 kGy) leads to an increasing conductivity of both *C*- and *2C*-samples in proportion to the absorbed dose; the conductivity decreases on cooling in temperature region of 100 – 300 K. An anomaly increase of conductivity is observed in *C*-polytype samples on cooling in temperature range of the incommensurate phase existence (197 – 214 K). The X-ray irradiation causes the "blur" of that anomaly. It is established that the mechanism of hopping conductivity with variable hopping length takes place for both polytypes in temperature range of 125 – 175 K and the densities of localized states near the Fermi level (N_F) are determined. Under irradiation the density N_F increases from $3.7 \cdot 10^{18} \text{ eV}^{-1} \cdot \text{cm}^{-3}$ (*C*) and $6.9 \cdot 10^{18} \text{ eV}^{-1} \cdot \text{cm}^{-3}$ (*2C*) and exceeds the initial more than three times at $D = 2.7 \text{ kGy}$. Using the one-dimensional Kronig-Penney model, the role of incommensurate periodic potential in modification of electron band structure at creation the incommensurate phases in crystals is discussed.

1. Introduction

β -TlInS₂ crystals are the wide-gap semiconductor-ferroelectrics and belong to the class of low-dimensional thallium compounds TlMX₂ (M = Ga, In; X = Se, S, Te). At ambient conditions β -TlInS₂ crystals are characterized by $C2/c$ space symmetry group of the monoclinic crystal system; unit cell parameters are $a = 10.90$ Å, $b = 10.94$ Å, $c = 15.18$ Å, $\beta = 100.21^\circ$.^[1] Since TlInS₂ crystals are promising materials as detectors of electromagnetic radiation, their dielectric, optical, elastic properties, electric transport has been actively studied in numerous works.^[2–5] It was found a number of anomalies of photoconductivity, permittivity, ultrasonic wave propagation velocity and specific heat of TlInS₂ crystals which are due to the existence of phase transitions (PT) in them with the formation of both commensurate and incommensurate modulated structures in temperature range of 170 – 240 K (as also in isostructural analog TlGaSe₂ but in temperature range 100 – 160 K).^[2,6,7] However, despite numerous experimental studies, data on the characteristics and mechanisms of PT "paraelectric – incommensurate phase (IP)" and "IP – commensurate phase (CP)" in TlInS₂ are quite contradictory. For example, according to neutron diffraction data,^[8] modulation satellites in corresponding to IP are observed in temperature range of $T = 200 – 216$ K with a modulation vector $q(\delta, \delta, 0.25)$ ($\delta = 0.012$). From another side, the X-ray diffraction data in temperature range of $T = 194 – 214$ K indicate the formation of incommensurate waves with the wavevector $q(\mp\delta, 0, \pm 0.25)$ ($\delta = 0.04$) as the waves of static atomic displacements.^[1,9] It was suggested that the incommensurate atomic displacements occur in the a -direction of monoclinic unit cell so the wavelength of incommensurability is the irrational number $\lambda_a = 1/\delta = 22.72\dots$. According to that model atoms with the same value of Z -coordinate are displaced in the a - b -plane by the same amount, and the Z -component of displacement is characterized by $\lambda_c = 4c$.

To explain the discrepancy between neutron and X-ray diffraction data, as well as number of other contradictions, it was suggested take into account the existence of a number of polytypes in the β -TlInS₂ crystals - C , $2C$, $4C$ and $8C$ with the unit cell parameter $c = c'$, $2c'$, $4c'$, $8c'$ ($c' \approx 15$ Å), respectively.^[10,11] In particular, for TlInS₂ crystals of $2C$ polytype the absence of modulation satellites of IP and CP in temperature range of 170 – 300 K, which points to absence of incommensurate and commensurate modulation waves, unlike the C polytype, was demonstrated with four circle X-ray diffractometry method.^[9,12] Because of these differences of the C and $2C$ polytypes crystal lattice dynamics, it is crucial compare the transport characteristics of these polytypes, in particular, their electrical conductivity. Since the conductivity of TlInS₂ is

very sensitive to changes of the defect's concentration level,^[13–15] it is important to study the electrical conductivity of TiInS_2 *C* and *2C* polytypes at various doses of X-ray irradiation in temperature range of 100 – 300 K. The paper presents the results of such research.

2. Experimental procedure

The single-crystal samples of TiInS_2 *C* and *2C* polytypes grown by the Bridgman–Stockbarger method were used for electrical conductivity measurements. The elemental composition and stoichiometry of the samples were verified by a local elemental analysis technique using energy-dispersive X-ray spectroscopy EDX (the JEOL JEM-2100F TEM). The X-ray diffraction identification of *C* and *2C* polytypes were performed by using a diffractometer DRON-4-07 with a single-crystal goniometer head GP-15. The typical size of rectangular samples was (5x7x0.1) mm; the surfaces (5x7) mm coincided with the cleavage planes (001). Silver probes were applied on both two surfaces (7x0.1) mm using Vacuum spraying method. At that electrodes arrangement the conductivity was measured along a cleavage plane. The samples were placed in the cryostat chamber CS204AEX1-AL; the temperature of samples was controlled using the Lake Shore 331S controller. The range of measurements were performed in the cooling mode (in some cases - in heating mode too) with temperature step 2 K, the rate of temperature change was 1 K / min, the accuracy of maintaining the temperature was 0.1 K.

A DC voltage which was formed by a 12-bit analog-to-digital converter and a buffer amplifier was applied to the sample. The voltage variation on the sample was $\Delta U = (-5) - (+5)$ V. The current in the sample was converted to voltage using a current-voltage converter, and it was controlled using a 16-bit analog-to-digital converter. The measuring range of current (*I*) was depended on the resistance of the current-voltage converter (for example, for resistance 30 M Ω the maximum current was about 35 nA), and the minimal current value was determined by the input current of the converter (2 pA in our case). The current – voltage characteristic of the sample was measured at each temperature in the voltage range ΔU , on which the linear regions were distinguished in the low-voltage region $\Delta U_l \approx (-0.04) - (+0.04)$ V. The conductivity was calculated as $\sigma = (U / I)^{-1} (l / S)$ (*l* - length, *S* - surface area of sample) at two identical voltage values, but different in polarity; for further analysis the averaged conductivity value was used.

The irradiation of samples was performed by the radiation of the X-ray tube BHV-12 Pd (voltage 30 kV, current 50 mA). The spectrum of X-ray radiation includes the characteristic $K\alpha$ and $K\beta$ lines (photons energies were 21.2 keV and 23.8 keV, respectively), *L* - series lines (2.7–2.9 keV) and bremsstrahlung. The sample was placed parallel to the plane of the X-Ray tube

beryllium window at the distance of 7 cm. The radiation was directed perpendicular to the cleavage surface (5x7) mm and was absorbed in a layer of 0.1 mm thick. To achieve a uniform irradiation in volume, the samples were irradiated from two sides. The PTW 23342 soft X-ray ionization chamber has been used to measure the absorbed X-ray dose rate. The dose rate was 1.25 mGy/min when chamber was installed in place of the sample. Each sample was initially irradiated for 12 h (6h for each side) and subsequently for another 24 h (12h for each side) so that the absorbed doses were 0.9 and 2.7 KGy, respectively.

3. Experimental Results

Figure 1 shows typical temperature dependences $\sigma(T)$ for samples of C-polytype TlInS₂ crystals both pristine and irradiated. For the unirradiated C-samples under cooling in temperature range of 255 – 290 K an exponential dependence $\sigma(T)$ with the activation energy of the charge carriers $E_a = 0.65 \pm 0.04$ eV is observed.

Figure 1. The dependence $\sigma(T)$ for C-samples TlInS₂. The activation energies: $E_a = 0.65 \pm 0.04$ eV (pristine), $E_a = 0.53 \pm 0.04$ eV (0.9 kGy), $E_a = 0.44 \pm 0.04$ eV (2.7 kGy)

At $T < 250$ K the deviation of $\sigma(T)$ from exponential was increasingly prominent, so the curve is flat at temperatures 214 - 217 K. Surprisingly, the further cooling is accompanied by an increase of conductivity, but already at 195 – 200 K the dependence $\sigma(T)$ reaches the maximum of the increase. Finally, at the $T < 195$ K the electrical conductivity monotonically decreases. Thus,

on cooling in the range of 195 – 214 K, in which the IP order parameter linearly increases,^[1] the dependence $\sigma(T)$ exhibits temperature behaviour anomalous for semiconductors. In contrast, upon subsequent heating of the samples, cooled to 100 K, in the temperature range of 195 K $\rightarrow$ 214 K the conductivity was rising monotonically. Figure 1 also presents the $\sigma(T)$ dependences on cooling for irradiated C-samples under two X-ray absorbed doses. First, there an increasing trend in the conductivity with absorbed dose growing was observed. It should be noted that as the absorbed dose increases, the anomaly on $\sigma(T)$ dependence on cooling in the range of 195 - 214 K is "blurred", so for the dose $D = 2.7$ kGy the increase of the conductivity in that temperature range is practically not observed. For irradiated samples, at $T = 245$ K – 300 K on the $\sigma(T)$, there are also exponential regions. As the absorbed doses increases, the activation energy decreases: $E_a = 0.53 \pm 0.04$ eV for $D = 0.9$ kGy and $E_a = 0.44 \pm 0.04$ eV for $D = 2.7$ kGy.

In Figure 2 the $\sigma(T)$ dependences are shown for samples of 2C-polytype TlInS₂ crystals. For 2C-samples $\sigma(T)$ dependences are substantially different: in the entire temperature range on cooling the conductivity decreases monotonically including the range of 195 – 217 K.

Figure 2. The dependence $\sigma(T)$ for 2C-samples TlInS₂. The activation energies: a) $T = 200 - 255$ K $E_a(1) = 0.51 \pm 0.04$ eV (pristine), $E_a(1) = 0.40 \pm 0.04$ eV (0.9 kGy); $E_a(2) = 0.31 \pm 0.04$ eV (2.7 kGy); b) $T = 255 - 300$ K $E_a(2) = 0.20 \pm 0.04$ eV (pristine), $E_a(2) = 0.13 \pm 0.04$ eV (0.9 kGy), $E_a(2) = 0.12 \pm 0.04$ eV (2.7 kGy)

Two temperature regions with the various exponential dependences $\sigma(T)$ are distinguished in temperature range 200 – 300 K for both unirradiated and irradiated samples: the range 255 – 300 K (1) with $E_a(1) = 0.51 \pm 0.04$ eV (unirradiated), $E_a(1) = 0.40 \pm 0.04$ eV (0.9 kGy) and $E_a(1) = 0.31 \pm 0.04$ eV (2.7 kGy), and the range 200 – 255 K (2) with $E_a(2) = 0.20 \pm 0.04$ eV (unirradiated), $E_a(2) = 0.13 \pm 0.04$ eV (0.9 kGy) and $E_a(2) = 0.12 \pm 0.04$ eV (2.7 kGy). The dependences $\sigma(T)$ on cooling and subsequent heating in contrast to *C*-samples are rather close and in range of 250 – 300 K are exponential with $E_a = 0.51 \pm 0.04$ eV and $E_a = 0.47 \pm 0.04$ eV, respectively. The absence of features on the $\sigma(T)$ dependence for 2*C*-samples in temperature range of 197 – 214 K, in which the IP exists in the *C*-polytype crystals, agrees well with the X-ray diffraction data regarding the absence of modulated structures in the TlInS₂ crystals of 2*C* polytype.^[8,11] As well as *C*-polytype, there is an electrical conductivity growing with increasing absorbed dose, and exponential dependences of $\sigma(T)$ at $T = 255$ K – 300 K with $E_a = 0.51 \pm 0.04$ eV (unirradiated), $E_a = 0.40 \pm 0.04$ eV (0.9 kGy) and $E_a = 0.31 \pm 0.04$ eV (2.7 kGy) are registries.

In summary, the main experimental results state: *i*) an anomaly behavior of conductivity in *C*-polytype samples at cooling in the temperature range of the IP existence (195 – 214 K), the X-ray irradiation causes the "blur" of that anomaly; *ii*) the conductivity of 2*C*-samples at cooling over the temperature range of 100 – 300 K is monotonically decreasing; *iii*) the X-ray irradiation leads to an increasing conductivity of both *C*- and 2*C*-samples.

4. Discussion

4.1. The conductivity parameters of the TlInS₂ crystals

It was previously found that high defective crystals TlInS₂ with layered structure are characterized by a high concentration of localized states ($\approx 10^{18}$ eV⁻¹ · cm⁻³) in the bandgap near the Fermi level, and electron hopping conductivity along localized states is realized in them.^[13,16] The exponential regions of the dependences $\sigma(T)$ for *C*-samples at 255 – 300 K and too exponential regions for 2*C*-samples at 200 – 255 K, 255 – 300 K correspond to conductivity with hopping activation energies of 0.1 – 0.7 eV. In such systems, upon further cooling one can expect the appearance of hopping conductivity with a variable hopping length. In that case, the temperature dependence of the conductivity takes the form $\sigma = \sigma_0 \exp(-BT^{-1/4})$ (Mott equation), where $B = 2a^{-3/4} (kN_F)^{-1/4}$ (a is radius of localization in electron wave function

$\psi \propto \exp(-r/a)$, k is Boltzmann's constant, N_F is the density of states near the Fermi level).^[17]

In order to clarify the existence of such conductivity the temperature dependence $\sigma(T)$ was analyzed in coordinates $\ln(\sigma/\sigma_0)$ vs. $T^{-1/4}$. Figure 3 and Figure 4 are presented these dependences for radiated and irradiated samples of *C*- and 2*C*-polytypes on cooling in temperature range 100 – 205 K.

Figure 3. The dependences $\ln(\sigma/\sigma_0)$ as function of $T^{-1/4}$ for *C*-samples TIInS₂

The approximating straight lines were constructed by the linear least squares method. As can be seen, for both *C* and 2*C* polytypes the linear dependences $\ln(\sigma/\sigma_0)$ vs. $T^{-1/4}$ are observed in some temperature intervals, which points to hopping conductivity with a variable hopping length there. Based on the slope of the straight lines, parameter B was determined and values of N_F has been estimated. The localization radius of $a = 1.4$ nm was used.^[16] The values of B and N_F , as well as the experimentally measured values of conductivity at 300 K for all types of samples are given in the Table 1. For the unirradiated *C*-samples $N_F = 3.7 \times 10^{18} \text{ eV}^{-1} \text{ cm}^{-3}$ was obtained, that

agrees well with result of measured on AC.^[12] After irradiation the concentration N_F increases and at $D = 2.7$ kGy exceeds the initial more than three times. A similar result was obtained for

Figure 4. The dependences $\ln(\sigma/\sigma_0)$ as function of $T^{-1/4}$ for 2C-samples TlInS₂

irradiated 2C-samples. It is important to note that the increase of N_F is accompanied by an increase of the sample's conductivity (see Table 1).

Table 1. The conductivity parameters of the TlInS₂ C and 2C polytypes

	D , kGy	C	2C
σ (300 K), $\Omega^{-1} \text{ cm}^{-1}$	unirradiated	5.1×10^{-8}	8.2×10^{-8}
	0.9	1.3×10^{-7}	1.6×10^{-7}
	2.7	2.9×10^{-7}	7.8×10^{-7}
B , $\text{K}^{1/4}$	unirradiated	65 ± 3	56 ± 3
	0.9	54 ± 3	48 ± 3
	2.7	47 ± 3	42 ± 3
$N(E_F)$, $\text{eV}^{-1} \text{ cm}^{-3}$	unirradiated	3.7×10^{18}	6.9×10^{18}
	0.9	7.7×10^{18}	1.3×10^{19}
	2.7	1.4×10^{19}	2.1×10^{19}

This testifies once again to the hopping conduction along localized states near the Fermi level in the TlInS₂ crystals.

4.2. The generation of defects in the TlInS₂ crystals under X-ray irradiation

Let us consider the possible channels of radiation defects generation in TlInS₂ crystals by photons with a highest energy of 21 keV (Pd $K_{\alpha,\beta}$ lines are the dominant components in spectrum of X-ray irradiation). The main mechanism of the of X-ray photons interaction with matter is atomic photoeffect if the photons energies below 100 keV^[18]. This is especially true for soft X-rays with energy $E(K\alpha) = 21$ keV. The photoelectrons with kinetic energies $E_e = E(K\alpha) - E_i$ are ejected from atoms as the result of ionization of the atomic electron shells (E_i - ionization potential of i -shell). In the case of the TlInS₂ crystals the range of the photoelectrons energies is 5 – 21 keV. At the next step, the photoelectrons undergo inelastic collisions with atoms, followed by secondary ionization of atoms. The energy transferred by a photoelectron to an atom of mass M_a can be estimated as $\Delta E_{max} = 4E_e m_e / (M_a + m_e)^2$, m_e - mass of the electron.^[19] For sulphur atom (the lightest atoms in the crystal TlInS₂, $M_a(S) \approx 5.9 \times 10^4 m_e$) it is $\Delta E_{max} \approx 1,4$ eV, while in semiconductors with ionic-covalent bonds the energy of atom's exit from lattice point is not less than 7 – 10 eV.^[20]

Therefore, at under-threshold irradiation the impact elastic-shifting mechanism of radiation defects creation in TlInS₂ does not work. But in that case the major role in the generation of defects plays the impurity atoms charged. The concentration of defects in unirradiated TlInS₂ crystals is high enough ($\approx 10^{18} \text{ cm}^{-3}$), and significant part of them is caused by impurities that are incorporated into the crystal lattice at the stage of crystal growth.^[19] Then, ionization of atom in the regular position of the crystal lattice (when the charged impurity atom is in certain vicinity of it) is accompanied by the Coulomb interaction of created ion with the impurity atom. As a result, an atom exits to the internode site and forms a vacancy with a fairly high probability.^[20] As shown,^[19] it is most probable for TlInS₂ crystals the arrangement of impurity atoms in the centre of the InS₄ octahedra at replacement of In atoms. Therefore, the ionization of sulphur atoms is accompanied by the appearance of anionic sulphur vacancies. In this case the creation of neutral complexes formed by anionic vacancies, charged impurity atoms and sulphur atoms in interstitials is possible. Unfortunately, we are not aware of papers in which the classification of defects in TlInS₂ crystals have been performed and their quantitative parameters presented. However, above qualitative

consideration shows that in TiInS_2 crystals at under-threshold irradiation there may be a rather effective impurity-ionization mechanism of intrinsic defect formation.

4.3. The one-dimensional model of the static modulation waves effect on the band structure

An interesting experimental result is an increasing of C -samples conductivity on cooling in temperature range of incommensurate phase existence 195 – 214 K. It should be noted that an increasing the TiInS_2 conductivity on cooling was reported earlier,^[16] however, the effect was observed in temperatures of 240 – 270 K, i.e. in the paraelectric rather than incommensurate phase. The fact the increase of conductivity on cooling C -samples begins at the appearance of IP (214 K) and finishes at the IP – CP PT (197 K) indicates that the presence of incommensurate displacement waves with the wave vector $\mathbf{q}(\delta, 0, 0.25)$ ($\delta = 0.04$) effects noticeably on the electrons transport. That influence can be associated with the appearance in IP an additional potential with the wave vector $\mathbf{q}(\delta, 0, 0.25)$, which superimposes on the periodic potential of the crystal lattice.

Figure 5. The rectangular Kroning-Penney and periodic modulation potentials

For this assumption verification we consider the following simple model of band structure with static modulation waves in crystal lattice. The lattice was simulated with the one-dimensional rectangular Kroning-Penney potential $U(x)$ with the period equal to a , width of the well equal to b and the depth equal to U_0 . The presence of the incommensurate phase was simulated with the following potential:

$$V(x) = \lambda U_0 \left[\cos \left(\frac{2\pi(x+b)}{a} + A \cos \left(\frac{2\pi(x+b)}{c} \right) \right) - 1 \right], \quad (1)$$

where c is the wavelength of incommensurate potential, λ determines the relation between the amplitudes of rectangular potential and incommensurate one (Figure 5), A is the amplitude of the phase term. This term defines displacements of the perturbed potential respectively to the Kroning-Penney one, and it corresponds to the rate of incommensurability, and in the case of commensurability A is equal to 0.

Thus, the over-all potential can be presented as: $U_{full} = U + V$. In our model we consider the influence of incommensurate potential as a small perturbation $\lambda \ll 1$, so in the first correction of perturbation theory the energy is: $E = E_0 + \langle V \rangle$, where $\langle V \rangle = \langle \psi(x) | \hat{V} \psi(x) \rangle$. The procedure of evaluation electron energy spectra in Kroning-Penney model is well known.^[21,22] For calculation we used the model parameters $a = 4 \times 10^{-10}$ nm, $b = 0.5 \times 10^{-10}$ nm, $c = 22.8 a$, $U_0 = 25$ eV.

Figure 6. The dispersive curves for the first and second bands: solid line - non-perturbed, dashed-dotted – perturbed solution with $A = 0$ (CP), dashed - perturbed solution with $A = \pi$ (IP)

In Figure 6 the calculated dispersive curves for non-perturbed and perturbed ($A = 0$, i.e., commensurate phase, and $A \neq 0$ – incommensurate phase) are presented. As one can see, the addition of commensurate perturbation leads to shift of dispersive curves and to the change of band gaps. Firstly, it should be noted that the presence of the perturbed potential leads to shift of the dispersive curves down. Nevertheless, presence of the perturbation can lead to increase or to decrease of the bandgap. As an example, the presence of commensurate phase decreases the first band gap, while the incommensurate phase with $A \neq 0$ increases it. Contrary situation is observed

for the second bandgap – the commensurate phase leads to increase of the bandgap value, and the incommensurate phase with considered amplitude decreases it.

Let us further focus on the consideration of the second bandgap, where the general trend of decreasing of bandgap with the amplitude of incommensurability is expected. Figure 7 shows the dependence of the second band gap on the amplitude of the incommensurability for different values of the perturbation magnitude. As one can see, the bandgap decreases with the λ for the case of commensurability ($A = 0$). For each value of λ , the band gap monotonically decreases with the A until it reaches the value at which the averaging acting of phase term ($\Delta\phi = A \cos(2\pi(x + b)/c)$ in Eq. (1) is in antiphase to the unperturbed potential. The maximum reduction of the bandgap of IP respectively to CP is 1.7 eV for the case of $\lambda = 0.1$. Additionally, it should be noted that due to the symmetry of the perturbation, the rate of change of the bandgap with A is small close to $A = 0$, and it increases with the rise of A and slows down in vicinity of the minimum. Therefore, the effect of the incommensurability starts to be more significant after some threshold value of A . According to the model this threshold value depends on the λ , and for the maximum considered value ($\lambda = 0.1$), it may be estimated as $A = 0.1$.

Figure 7. The dependence of the second band gap on the amplitude of the incommensurability

The amplitude A which determines the value of incommensurate term in the total potential in fact characterizes the order parameter in the IP. Then an increase the order parameter in IP at cooling from 214 K to 197 K correlates with an increase the amplitude A ,^[1] and consequently, correlates with a decrease the band gap width in the temperature region of the IP existence. At IP – CP PT (197 K) amplitude $A \rightarrow 0$ and the band gap width increases again. Thus, the increase of conductivity on cooling from 214 K to 197 K and its decrease at further cooling can be associated with the changes of the band gap width when IP appears and decays. At first glance the

electron hopping mechanism of conductivity along localized states near the Fermi level is not directly related with the width band gap.

But the perturbation of energy diagrams and band gap due to the presence of IP phase leads to the modification of the hopping probability between two localized sites, which leads to modification of the involved in Mott equation. Specifically, the modifications of energy distribution results in variation of the energy of separation defining the probability in the case of equal-distance localization sites positions.^[23] We hope the proposed model will stimulate more complete calculations the effect of incommensurability on the conductivity of TlInS₂ crystals.

5. Conclusions

The conductivity of both unirradiated and irradiated TlInS₂ crystals of the *C* and 2*C* polytypes decreases on cooling in temperature range of 100 – 300 K. But for samples of the *C*-polytype in the temperature range of the existence of incommensurate phase (197 – 214 K) an increase of conductivity is observed, which is absent for samples of the 2*C*-polytype. The conductivity of samples irradiated by X-rays increases in proportion to the absorbed dose. In the temperature range of $\approx 125 - 175$ K the mechanism of hopping conductivity with variable hopping length is realized for both polytypes. Based on the Mott equation, the densities of localized states near the Fermi level were determined. Using the one-dimensional Kroning-Penney model, it is shown that the addition of an incommensurate periodic potential to the rectangular lattice potential leads to a shift of the dispersion dependences, while the gap of second band decreases with increasing amplitude of the incommensurate potential.

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