Edge States in p-n Junctions in Inverted Band HgTe Quantum Wells

S.U. Piatrusha*†, V.S. Khrapai*†, Z.D. Kvon‡§, N.N. Mikhailov‡, S.A. Dvoretsky‡, and E.S. Tikhonov*†

*Institute of Solid State Physics, Russian Academy of Sciences, 142432 Chernogolovka, Russian Federation
†Moscow Institute of Physics and Technology, Dolgoprudny, 141700 Russian Federation
‡Institute of Semiconductor Physics, Novosibirsk 630090, Russia
§Novosibirsk State University, Novosibirsk 630090, Russia

Abstract—We investigate current noise of lateral p-n junctions, electrostatically defined in 14 nm–wide HgTe-based quantum wells (QWs) with inverted band structure. Consistent with previous experiments on 8–10 nm QWs, the p-n junctions resistances are close to $h/2e^2$, indicating the edge states contribution to transport. Taking into account contacts heating, we find that the observed shot noise is suppressed compared to the diffusive value and is in reasonable agreement with prediction for one-dimensional edge states realized along the p-n junction. Our approach looks promising for the study of short quasi-ballistic edges in topological insulators (TIs).

I. INTRODUCTION

Theoretical prediction for the possible existence of gapless edge states on the boundary between a topologically nontrivial and a conventional insulators [1] has led to their experimental realization in several materials [2], [3]. Concerning the HgTe QWs with inverted band structure, edge transport was verified, e.g., via non-local measurements [4] or the visualisation of current density [5]. Despite extensive study, however, some fundamental aspects are still lacking understanding. Edge conductance values, close to the quantum $e^2/h$, were demonstrated only for the shortest edges no longer than few micrometers [2], [6]. Up to now there is no agreement on the dominant scattering mechanism, which leads to the linear length-dependence with the absent or weak dependence on temperature for the longer edges [7]. Our objective here is to implement noise measurements for the study of edge states.

The nature of edge conduction mechanism may be directly probed by the measurements of current fluctuations, which are induced by the scattering of electrons transmitted through the conductor. For example, for strictly one dimensional coherent conductor, the Fano-factor $F = S_I/2eI$ is directly related to the transmission via $F = 1 - T$. For a ballistic conductor shot noise vanishes, while in diffusive multi-channel regime $F = 1/3$. Despite the obvious potential of shot noise measurements, to the best of our knowledge there is only one experimental study considering current noise of the edge states [8]. The authors examined relatively long resistive edges and obtained $F$ between 0.1 and 0.3, qualitatively consistent with the later developed theory [9]. Up to now, vanishing shot noise – the direct consequence and evidence of ballistic transport, was never observed for edges with $R_{edge} \approx h/e^2$.

Recently, the edge states contribution [10], [11] was experimentally identified in the conductance of lateral $p-n$ junctions in 8–10 nm HgTe QWs [12]. Here, we investigate the current noise of such junctions, defined electrostatically in 14 nm HgTe QWs at $T = 0.5$ K. While for 8 nm QWs this is a low enough temperature to safely exclude the bulk shunt of edge states transport, an order of magnitude smaller bulk gap in 14 nm QWs requires even lower temperatures. We therefore intentionally limit ourselves to the discussion of short $p-n$ junctions. We demonstrate the importance of (i) minimizing the contacts resistance and (ii) hole-phonon scattering, characterized by the rate $\Sigma_{h-\text{ph}}$, in $p$-type conduction region. Our approach, provided $\Sigma_{h-\text{ph}}$ is known, may allow to infer the edge transport mechanism.

Theoretical values $F = 0$ and $F = 1/3$ [13] (or $F = \sqrt{3}/4$ in the case of strong electron-electron scattering) obtained for ballistic and diffusive conductors, respectively, hold assuming ideal boundary conditions for the electrons immediately at the sample ends, i.e. for reservoirs of infinite size with infinite electric and heat conductivities [14]. Experimentally, however, the measured signal may be significantly affected by overheating of the leads, which depends on its material, actual size and heat conductance. Qualitatively, in the presence of current flow, the Johnson-Nyquist noise is no longer constant with temperature for the longer edges [7]. Our objective here is to implement noise measurements for the study of edge states.

The nature of edge conduction mechanism may be directly probed by the measurements of current fluctuations, which are induced by the scattering of electrons transmitted through the conductor. For example, for strictly one dimensional coherent conductor, the Fano-factor $F = S_I/2eI$ is directly related to the transmission via $F = 1 - T$. For a ballistic conductor shot noise vanishes, while in diffusive multi-channel regime $F = 1/3$. Despite the obvious potential of shot noise measurements, to the best of our knowledge there is only one experimental study considering current noise of the edge states [8]. The authors examined relatively long resistive edges and obtained $F$ between 0.1 and 0.3, qualitatively consistent with the later developed theory [9]. Up to now, vanishing shot noise – the direct consequence and evidence of ballistic transport, was never observed for edges with $R_{edge} \approx h/e^2$.

Recently, the edge states contribution [10], [11] was experimentally identified in the conductance of lateral $p-n$ junctions in 8–10 nm HgTe QWs [12]. Here, we investigate the current noise of such junctions, defined electrostatically in 14 nm HgTe QWs at $T = 0.5$ K. While for 8 nm QWs this is a low enough temperature to safely exclude the bulk shunt of edge states transport, an order of magnitude smaller bulk gap in 14 nm QWs requires even lower temperatures. We therefore intentionally limit ourselves to the discussion of short $p-n$ junctions. We demonstrate the importance of (i) minimizing the contacts resistance and (ii) hole-phonon scattering, characterized by the rate $\Sigma_{h-\text{ph}}$, in $p$-type conduction region. Our approach, provided $\Sigma_{h-\text{ph}}$ is known, may allow to infer the edge transport mechanism.

Theoretical values $F = 0$ and $F = 1/3$ [13] (or $F = \sqrt{3}/4$ in the case of strong electron-electron scattering) obtained for ballistic and diffusive conductors, respectively, hold assuming ideal boundary conditions for the electrons immediately at the sample ends, i.e. for reservoirs of infinite size with infinite electric and heat conductivities [14]. Experimentally, however, the measured signal may be significantly affected by overheating of the leads, which depends on its material, actual size and heat conductance. Qualitatively, in the presence of current flow, the Johnson-Nyquist noise is no longer constant with temperature for the longer edges [7]. Our objective here is to implement noise measurements for the study of edge states.

The nature of edge conduction mechanism may be directly probed by the measurements of current fluctuations, which are induced by the scattering of electrons transmitted through the conductor. For example, for strictly one dimensional coherent conductor, the Fano-factor $F = S_I/2eI$ is directly related to the transmission via $F = 1 - T$. For a ballistic conductor shot noise vanishes, while in diffusive multi-channel regime $F = 1/3$. Despite the obvious potential of shot noise measurements, to the best of our knowledge there is only one experimental study considering current noise of the edge states [8]. The authors examined relatively long resistive edges and obtained $F$ between 0.1 and 0.3, qualitatively consistent with the later developed theory [9]. Up to now, vanishing shot noise – the direct consequence and evidence of ballistic transport, was never observed for edges with $R_{edge} \approx h/e^2$.

Recently, the edge states contribution [10], [11] was experimentally identified in the conductance of lateral $p-n$ junctions in 8–10 nm HgTe QWs [12]. Here, we investigate the current noise of such junctions, defined electrostatically in 14 nm HgTe QWs at $T = 0.5$ K. While for 8 nm QWs this is a low enough temperature to safely exclude the bulk shunt of edge states transport, an order of magnitude smaller bulk gap in 14 nm QWs requires even lower temperatures. We therefore intentionally limit ourselves to the discussion of short $p-n$ junctions. We demonstrate the importance of (i) minimizing the contacts resistance and (ii) hole-phonon scattering, characterized by the rate $\Sigma_{h-\text{ph}}$, in $p$-type conduction region. Our approach, provided $\Sigma_{h-\text{ph}}$ is known, may allow to infer the edge transport mechanism.

Theoretical values $F = 0$ and $F = 1/3$ [13] (or $F = \sqrt{3}/4$ in the case of strong electron-electron scattering) obtained for ballistic and diffusive conductors, respectively, hold assuming ideal boundary conditions for the electrons immediately at the sample ends, i.e. for reservoirs of infinite size with infinite electric and heat conductivities [14]. Experimentally, however, the measured signal may be significantly affected by overheating of the leads, which depends on its material, actual size and heat conductance. Qualitatively, in the presence of current flow, the Johnson-Nyquist noise is no longer constant with temperature for the longer edges [7]. Our objective here is to implement noise measurements for the study of edge states.

The nature of edge conduction mechanism may be directly probed by the measurements of current fluctuations, which are induced by the scattering of electrons transmitted through the conductor. For example, for strictly one dimensional coherent conductor, the Fano-factor $F = S_I/2eI$ is directly related to the transmission via $F = 1 - T$. For a ballistic conductor shot noise vanishes, while in diffusive multi-channel regime $F = 1/3$. Despite the obvious potential of shot noise measurements, to the best of our knowledge there is only one experimental study considering current noise of the edge states [8]. The authors examined relatively long resistive edges and obtained $F$ between 0.1 and 0.3, qualitatively consistent with the later developed theory [9]. Up to now, vanishing shot noise – the direct consequence and evidence of ballistic transport, was never observed for edges with $R_{edge} \approx h/e^2$.

Recently, the edge states contribution [10], [11] was experimentally identified in the conductance of lateral $p-n$ junctions in 8–10 nm HgTe QWs [12]. Here, we investigate the current noise of such junctions, defined electrostatically in 14 nm HgTe QWs at $T = 0.5$ K. While for 8 nm QWs this is a low enough temperature to safely exclude the bulk shunt of edge states transport, an order of magnitude smaller bulk gap in 14 nm QWs requires even lower temperatures. We therefore intentionally limit ourselves to the discussion of short $p-n$ junctions. We demonstrate the importance of (i) minimizing the contacts resistance and (ii) hole-phonon scattering, characterized by the rate $\Sigma_{h-\text{ph}}$, in $p$-type conduction region. Our approach, provided $\Sigma_{h-\text{ph}}$ is known, may allow to infer the edge transport mechanism.
obtained results for the noise of $p-n$ junctions.

II. SAMPLES AND MEASUREMENT TECHNIQUE

Our samples are based on 14 nm wide (112) Cd-HgTe/HgTe/CdHgTe QWs grown by molecular beam epitaxy, with mesas shaped by wet etching and covered with a SiO$_2$/Si$_3$N$_4$ insulating layer, see Ref. [19] for the details. Metallic Au/Ti top gates enable us to tune the 2D system across the charge neutrality point by means of field effect. Ohmic contacts are achieved by a few second In soldering in air, providing a typical resistance of the ungated mesa arms $\approx 5 \text{k}\Omega$ at low $T$. The experiment was performed in a liquid $^3$He insert with a bath temperature $T = 0.5 \text{K}$. Transport measurements were performed in a two-terminal or multi-terminal configurations with a low-noise 100 M$\Omega$ input resistance preamplifier. The voltage fluctuations were measured within a frequency band $20-24 \text{MHz}$ for sample S1 and $8.5 - 9.5 \text{MHz}$ for sample S2 on a $R_0 = 10 \text{k}\Omega$ load resistor, connected in parallel with a resonant tank circuit. The signal was amplified by a home-made 10 dB low-temperature amplifier (LTAmpl), followed by a 3 x 25 dB room-$T$ amplification stage, and measured with a power detector (not shown in fig. 1). The setup was calibrated via the Johnson-Nyquist thermometry. Below we present the results obtained on two samples which demonstrate similar behavior reproducible with respect to thermal recycling. We note that transport measurements were also performed on two more samples with similar results.

III. TRANSPORT MEASUREMENTS

The samples layouts are shown schematically in fig. 1a,b with 2D leads coloured in gray and electrostatic gates in yellow. Sample S1 is equipped with one large gate, while sample S2 is equipped with two smaller gates, only one of which (labeled with G) was used in the present experiment. Via indexed letters Ci we denote 2D mesa leads (see the sketch of the whole sample S2 in the inset of fig. 1b). Contact labeled with N was used for noise measurements. From four-point resistance measurements at gate voltages $V_g = 0 \text{V}$ and $V_g = -6 \text{V}$ we extract the electron (hole) resistivities $\rho_e$ ($\rho_h$) of 230 (2000) $\Omega$ for sample S1 and 240 (3200) $\Omega$ for sample S2.

In fig. 2 we plot the gate voltage dependencies of the two terminal linear response resistances ($R_{2t}$) for several contacts on both samples S1 and S2. In these measurements all contacts, except for the studied one, are grounded. At $V_g = 0 \text{V}$ the measured value, $R_{2t,e}$, reflects the resistance of 2D mesa leads and ohmic contacts at the In/2DEG interface (which we denote via $R_{\text{Cl/N,ohmic}}$). It is on the order of a few kilohms for most of the contacts. However, contacts C4 and C5 of sample S2 were not working properly, due to poor In soldering, and contacts C6 and C7 of sample S2, as well as contact C3 of sample S1, had relatively large resistances of approximately 20 k$\Omega$, 70 k$\Omega$ and 20 k$\Omega$, respectively.

At negative enough $V_g$, when p-type conduction regime is set up in the mesa region under the gate, the measured resistance, $R_{2t,h}$, is determined simultaneously by ohmic contacts, 2D leads, p-type conduction area under the gate and $p-n$ junctions, formed in the mesa under the gate edge. For all samples studied, $R_{2t,h}$ is almost $V_g$-independent, though with visible fluctuations, at $V_g < -5 \text{V}$. While both $R_{2t,e}$ and $R_{2t,h}$ values may be affected by the unknown ohmic contact resistance, their difference eliminates this uncertainty and provides information about $p-n$ junctions resistances. We note that for most contacts for all samples the difference $R_{2t,h} - R_{2t,e}$ is always close to $R_Q \equiv h/2e^2$, exceeding it by several kilohms, which may correspond to the resistance of under-the-gate p-type conduction region.

Assuming all $p-n$ junctions have resistance $R_{pn} = R_Q$ and using measured values of $\rho_{e,h}$, for geometry corresponding to mesa mask we calculate the two terminal resistance (for both n- and p-type conduction under the gate) for different contacts, and compare it with experimental values. The calculated values are illustrated in fig. 3 by thick dashed straight lines. For contact N on sample S1 thus calculated resistance is perfectly consistent with the measured value both at $V_g = 0 \text{V}$ and $V_g = -6 \text{V}$ in assumption of vanishing corresponding ohmic contact resistance $R_{\text{N,ohmic}} = 0 \Omega$. For contact C4
on sample S1 both measured resistances are greater than calculated values by the same amount of \( \approx 2.8 \, k\Omega \), which most likely reflects \( R_{C4,\text{ohmic}} = 2.8 \, k\Omega \). This consistency shows that the resistance of \( p-n \) junctions in our devices is indeed close to resistance quantum. For contact N on sample S2, while the agreement for \( n \)-type conduction is good with negligible small \( R_{N,\text{ohmic}} = 0 \, \Omega \), the measured resistance for \( p \)-type conduction under the gate is by \( \sim 4 \, k\Omega \) smaller than the calculated one. This might indicate the bulk of \( p-n \) junction contribution to transport. We note that observation \( R_{pn} \approx R_Q \) holds also for samples where noise measurements were not performed.

The values \( R_{pn} \approx R_Q \) do not necessarily imply that conduction through \( p-n \) junctions is realized via two ballistic single-channel edge states. In the following we study shot noise at large negative \( V_g \) and compare obtained results with two limit predictions, corresponding to either ballistic or diffusive conduction across the \( p-n \) junction.

IV. Noise measurements

A. Contacts heating

First, in order to take contacts heating into account, we set \( V_g = 0 \, V \) and study 2D leads heating in response to the flowing current. For long enough conductors, when local electron temperature is well defined, shot noise is represented by the Johnson-Nyquist relation with electron temperature averaged over the whole sample. Experimental results, expressed in terms of noise temperature \( T_N = S_1 R/4 k_B \), are shown in Fig. 2 for sample S2 by circles. To demonstrate the influence of inelastic e-ph scattering, by dotted line we show the prediction for the case, when e-ph scattering is absent. The obvious \( T_N \) suppression reflects the fact that thermal relaxation of electrons is realized not only by electronic diffusion towards the ohmic contacts, but also by electron-phonon coupling. Local power flow between electron and phonon systems is given by

\[
P_{e-\text{ph}} = \Sigma_{e-\text{ph}}(T^\alpha - T_0^\alpha),
\]

where \( T = T(x,y) \) – position-dependent electronic temperature, \( T_0 \) – bath temperature and \( \Sigma_{e-\text{ph}} \) is material-dependent electron-phonon coupling coefficient. Exponent \( \alpha \) characterizes the heat transfer mechanism and in general varies in the range \( \alpha \approx 3 - 6 \) \cite{20}. To determine the exact values of \( \Sigma_{e-\text{ph}} \) and \( \alpha \), we first numerically solve the two-dimensional stationary heat diffusion equation

\[
-\nabla(\alpha \nabla T) = Q_{\text{Joule}} - P_{e-\text{ph}}
\]

along with Poisson’s equation, for the sample shape corresponding to the lithographic mesa pattern. Here \( Q_{\text{Joule}} = J \cdot E \) – local Joule heat power source, \( E = 2.44 \times 10^{-8} \, W/\Omega \) – the Lorenz number, and heat conduction is assumed to satisfy the Wiedemann-Franz law

\[
\alpha = \sigma L T.
\]

Using thus obtained electronic temperature profile, we calculate the noise temperature of the sample via

\[
T_N = \frac{\int T(x,y) Q_{\text{Joule}} \, dx \, dy}{\int Q_{\text{Joule}} \, dx \, dy},
\]

with integration taken over the whole mesa.

We find that in the bias voltage range of few millivolts experimental data are best fitted with \( \alpha \approx 3 \) (see Fig. 2). The corresponding value of \( \Sigma_{e-\text{ph}} = 16 \, mW/m^2K^3 \) is the same for both samples S1 and S2 and is reproducible with respect to thermal recycling. Passing, we note that for larger bias voltages up to \( \sim 100 \, mV \) the data are perfectly consistent with \( \alpha = 4 \) and \( \Sigma_{e-\text{ph}} \approx 7 \, mW/m^2K^4 \). Both exponents \( \alpha = 3 \) and \( \alpha = 4 \) may correspond to the 2D acoustic phonon cooling mechanism and were observed, for example, in graphene \cite{21}, \cite{22}.

B. Shot noise of \( p-n \) junctions

We next discuss results obtained for large negative gate voltages, when \( p \)-type conduction regime is set up in the mesa region under the gate. Here, \( p-n \) junctions are formed in the mesa region close to the gate edges. As discussed above, these \( p-n \) junctions are connected to ohmic contacts not only via 2D leads with \( n \)-type conduction, but in part also via more resistive \( p \)-type conduction region under the gate. Unfortunately, the geometry of our samples doesn’t allow to accurately determine the rate of hole-phonon energy relaxation \( \Sigma_{h-\text{ph}} \). We are not aware of any systematic studies of \( \Sigma_{h-\text{ph}} \) in HgTe QWs, however, there are some indications from transport-based measurements of energy relaxation that the hole-phonon energy relaxation is significantly enhanced compared to \( \Sigma_{e-\text{ph}} \) \cite{23}. In the following we compare experimentally obtained results with model predictions for various values of \( \Sigma_{h-\text{ph}} \).

Our model geometry (see Fig. 3) corresponds to mesa mask geometry with dotted rectangular indicating the gate position.
Yellow area is the p-type conduction region under the gate with hole resistivity $\rho_h$ and hole-phonon coupling $\Sigma_{h\rightarrow ph}$; gray areas are the n-type conduction 2D leads with electron resistivity $\rho_e$ and electron-phonon coupling $\Sigma_{e\rightarrow ph}$. Shaded rectangles at the edge of the gate model $p-n$ junctions with conductance $G = G_Q = 2e^2/h$. We note that calculation results do not depend on the length of the $p-n$ junction area as long as it is reasonably short, thus allowing to neglect phonon scattering in this region. We set boundary conditions by defining temperatures $T = T_0$ at the ohmic contacts. The bias voltage, $V$, applied to the N-contact, defines the current through each mesa arm, allowing the temperature map to be obtained from the combined solution of Poisson’s and heat diffusion equations. This is enough to calculate the noise temperature of the sample as we describe below.

Generally, noise power of the current fluctuations in the non-interacting scattering theory is determined by two inputs [24]:

$$S = S_{eq} + S_{non-eq},$$

where the first term is the analog of the equilibrium noise contribution, present for any conductor –

$$S_{eq} = G_Q \sum_n \int dE \{ T_n [f_L(1-f_L) + f_R(1-f_R)] \},$$

and the second term is the non-equilibrium or shot noise contribution –

$$S_{non-eq} = G_Q \sum_n \int dE \{ T_n(1-T_n) (f_L - f_R)^2 \}.$$

We consider two limit predictions for the noise of our $p-n$ junctions. The first one corresponds to ballistic conduction across the $p-n$ junction (along two mesa edges), when its current spectral density is completely determined by $S_{eq}$:

$$S_{ball} = 2G_Q \int dE [f_L(1-f_L) + f_R(1-f_R)].$$

We assume electronic distribution functions at the boundaries of the $p-n$ junction to be Fermi-Dirac with temperatures $T_L$ and $T_R$, that are obtained numerically from the solution of heat diffusion equation. Such an assumption ensures the proper heat flow outwards the $p-n$ junction. The current spectral density of the $p-n$ junction is thereby given by

$$S_{ball} = 2k_B(T_L + T_R)G_Q.$$

Another limit is realized when conduction across the $p-n$ junction is diffusive. Here, current spectral density is determined both by equilibrium and shot noise contributions, and can be calculated via eq. (1):

$$S_{diff} = 4k_BTNG_Q.$$

The noise of contacts is also calculated via eq. (1). For both limits we treat 2D leads and $p-n$ junctions as uncorrelated noise sources and calculate the noise temperature of the sample using standard formalism [24]. We note that the two-terminal differential resistance of our samples at large negative gate voltages is almost bias-independent, with changes on the order of few percent. This behaviour is in contrast with behaviour of typical semiconductor $p-n$ junctions and may serve as an additional indication for the edge states shunting the bulk of the $p-n$ junctions.

Experimental results (symbols), obtained for sample S1 at $V_g = -6.5$ V and for sample S2 at $V_g = -6$ V, are shown in fig. 4a,b and fig. 4c,d, respectively (note a wider bias range for the sample S2). These results are almost $V_g$-independent for large negative $V_g$. We emphasize that the data slope $dS_I/d(2eI) \approx 0.15$ should not be confused with the Fano-factor of the $p-n$ junctions, since the measured signal is comprised of both the junction and the contact noise inputs. The fits for ballistic and diffusive conduction across the $p-n$ junctions are shown in fig. 4a,c and fig. 4b,d by dashed and dotted lines, respectively. Since $\Sigma_{h\rightarrow ph}$ is unknown, we compare experimental results with model predictions for different strength of hole-phonon coupling. We note that for the values of $\Sigma_{h\rightarrow ph} \approx \Sigma_{e\rightarrow ph}$ the model prediction is much
greater than experimentally observed value even in the ballistic case, indicating that $\Sigma_{h_{\text{ph}}} > \Sigma_{e_{\text{ph}}}$. While for the ballistic case the model is in agreement with experimental data for the relatively reasonable values of $\Sigma_{h_{\text{ph}}}(S1) = 0.14 \text{W/m}^2$ and $\Sigma_{e_{\text{ph}}}(S2) = 0.23 \text{W/m}^2$, for the diffusive case the model prediction is still greater than experimentally observed values even for the three orders of magnitude stronger hole-phonon couplings and only approaches it at further $\Sigma_{h_{\text{ph}}}$ increase. Although not providing definite value for the shot noise of $p-n$ junctions, the presented data suggest that it is suppressed compared to the diffusive value and is in reasonable agreement with prediction for one-dimensional edge states realized along the p-n junction.

### V. Conclusion

In summary, we studied the current noise of lateral $p-n$ junctions, electrostatically defined in 14 nm–wide HgTe-based QWs. Resistance measurements indicate that the transport across the junction may be realized via two edge channels with resistance of each close to $h/e^2$. We take into account the contacts heating effect and compare experimental results for the shot noise with the model predictions for ballistic and diffusive junctions. Due to the unknown hole-phonon coupling our conclusion is not definitive, however, the obtained results support the presence of one-dimensional edge states in the p-n junction. Our approach looks promising for the study of short edges of 2D TIs.

### Acknowledgment

We thank D.V. Shovkun for fruitful discussions. This work was supported by the Ministry of Education and Science of the Russian Federation Grant No. 14.Y26.31.0007, the RFBR Grants No. 16-32-00869 and No. 15-02-04285.

### References

1. C. L. Kane and E. J. Mele, *Phys. Rev. Lett.*, vol. 95, p. 146802, 2005.
2. M. König, S. Wiedmann, C. Brüne, A. Roth, H. Buhmann, L. W. Molenkamp, X.-L. Qi, and S.-C. Zhang, *Science*, vol. 318, pp. 5851, pp. 766–770, 2007.
3. I. Knez, R.-R. Du, and G. Sullivan, *Phys. Rev. Lett.*, vol. 107, p. 136603, 2011.
4. A. Roth, C. Brüne, H. Buhmann, L. W. Molenkamp, J. Maciejko, X.-L. Qi, and S.-C. Zhang, *Science*, vol. 325, no. 5938, pp. 294–297.
5. K. C. Nowack, E. M. Spanton, M. Baenninger, M. König, J. R. Kirtley, B. Kalisky, C. Ames, P. Leubner, C. Brüne, H. Buhmann, L. W. Molenkamp, D. Goldhaber-Gordon, and K. A. Moler, *Nature Materials*, vol. 12, no. 9, pp. 787–791, 2013.
6. E. B. Olshanetsky, Z. D. Kvon, G. M. Gusev, A. D. Levin, O. E. Raichev, N. N. Mikhailov, and S. A. Dvoretsky, *Phys. Rev. Lett.*, vol. 114, p. 126802, 2015.
7. G. M. Gusev, Z. D. Kvon, E. B. Olshanetsky, A. D. Levin, Y. Krupko, J. C. Portal, N. N. Mikhailov, and S. A. Dvoretsky, *Phys. Rev. B*, vol. 89, p. 125305, 2014.
8. E. S. Tikhonov, D. V. Shovkun, V. S. Khrapai, Z. D. Kvon, N. N. Mikhailov, and S. A. Dvoretsky, *JETP Letters*, vol. 101, no. 10, pp. 708–713, 2015.
9. P. P. Aseev and K. E. Nagaev, *Phys. Rev. B*, vol. 94, p. 045425, 2016.
10. L. B. Zhang, K. Chang, X. C. Xie, H. Buhmann, and L. W. Molenkamp, *New Journal of Physics*, vol. 12, no. 8, p. 083058, 2010.
11. Y.-T. Zhang, J. Song, and Q.-F. Sun, *Journal of Physics: Condensed Matter*, vol. 26, no. 8, p. 085301, 2014.