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Anisotropic spin interference in InGaAs/InAlAs rectangular loop arrays

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Abstract

We report the experimental detection of the anisotropic spin-orbit interaction (SOI) in InGaAs/InAlAs quantum wells, using spin interference experiments in arrays of rectangular loops with their sides aligned to the $[110]$ and $[1\bar{1}0]$ crystallographic directions. While the gate voltage is tuned, the time reversal Aharonov-Casher (TRAC) oscillations exhibit higher frequencies when the loops have their longer side along the $[110]$ direction, clearly highlighting the anisotropy of the SOI. We find that a simple spin interferometer model, including both the Rashba and the Dresselhaus SOIs, reproduces qualitatively the TRAC oscillations.

Key words: spin-orbit interaction, quantum interference, AAS oscillations, Aharonov-Casher effect, InGaAs

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The emerging field of spintronics [1] that aims to utilize the electron spin degree of freedom to create a novel generation of electronic devices has attracted much of interest in the past decade. A special attention has been paid to the spin-orbit interaction (SOI), especially in III-V heterostructures, as it provides an elegant way to manipulate the electrons' spin through an external electric field. Of particular interest is the anisotropic interplay between the Rashba and the Dresselhaus contributions to the SOI, which respectively stem from the asymmetry of the vertical confining potential and the lack of inversion symmetry of the crystal lattice [2]. Indeed, considering a (001) oriented III-V heterostructure, the spin-orbit (SO) Hamiltonian H_{SO} , including the Rashba and the linear Dresselhaus terms, can be written as [3]

$$H_{SO} = \alpha(\sigma_x k_y - \sigma_y k_x) + \beta(\sigma_x k_x - \sigma_y k_y), \quad (1)$$

where $\mathbf{k}$ is the electron wave vector, $\boldsymbol{\sigma}$ is the vector of the Pauli matrices, and α and β are the Rashba and the Dresselhaus SO parameters. For electrons moving along the $[110]$ and the $[1\bar{1}0]$ crystallographic directions, the effective magnetic fields associated with the Rashba and the Dresselhaus terms are then expected to be aligned together, perpendicularly to $\mathbf{k}$. Consequently, the total SO parameter is given by $\alpha + \beta$ along the $[110]$ direction and by $\alpha - \beta$ along the $[1\bar{1}0]$. This interplay generates a particularly interesting configuration when $\alpha = \beta$, as the SOI vanishes along the $[1\bar{1}0]$ direction, leading to the formation of a persistent spin helix [4].

Quantum interference experiments provide tools to investigate the SO properties in two-dimensional electron systems (2DESs). In particular, low temperature T magnetotransport measurements in arrays of mesoscopic loops show Al'tshuler-Aronov-Spivak (AAS) oscillations [5] whose amplitude can be tuned by means of an external gate voltage V_g through the SOI [6, 7, 8, 9]. This modulation of the AAS oscillations amplitude has been interpreted as a demonstration of the time reversal Aharonov-Casher (TRAC) effect [6, 7, 8, 9, 10]. Here, we study the anisotropic interplay between the Rashba and Dresselhaus terms by investigating the TRAC effect in arrays of InGaAs/InAlAs rectangular loops with their sides aligned to the $[110]$ and $[1\bar{1}0]$ crystallographic directions. We find that the TRAC oscillations exhibit a higher frequency when the loops have their longer side along the $[110]$ direction, clearly demonstrating an anisotropy of the total SOI in the 2DES. The oscillating behaviour of the TRAC oscillations is successfully described by a simple spin interference (SI) model, indicating that the SO anisotropy is consistent with the interplay of the Rashba and Dresselhaus terms.

The heterostructures used in this work are a 10 nm thick $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ quantum wells grown by MOCVD on (001) InP substrate (see Fig. 1(a)), and are referred to as KH1 ($N_1 = 4 \times 10^{18} \text{ cm}^{-3}$ and $N_2 = 0 \text{ cm}^{-3}$)

and KH3 ($N_1 = N_2 = 2 \times 10^{18} \text{ cm}^{-3}$). In the context of the anisotropic interplay of the Rashba and Dresselhaus terms, the definition of the crystallographic axes has to be done carefully [11]. We define the indices putting group III elements at [000] and group V elements at $\frac{a}{4}[111]$ in the primitive cell, where a is the lattice parameter. We define the x , y , and z axes along the [100], [010], and [001] crystallographic directions, respectively, using the above definition. The definition we use here is the same as the one used in the semiconductor industry. We note that the information provided by the wafer supplier was double checked by studying the wet etched grooves' profiles of the InP substrate [12] (see Fig. 1(b)). We further define that the [001] direction is pointing upward from the samples' surface (Fig. 1(a)). Using this definition, the doping profiles of the structures investigated here generate a positive electric field E_z (i.e. in the [001] direction) in the quantum wells when no gate voltage is applied to the systems. This positive E_z leads to a positive value of α . Note that in the case of the KH1 heterostructure, α is larger due to the stronger asymmetry of the doping profile. The Dresselhaus parameter β , along the [100] direction, is given, within the $\mathbf{k} \cdot \mathbf{p}$ framework, by $\langle b_{41}^{6c6c} \rangle \langle k_z^2 \rangle$, where k_z is the confinement wave number and $\langle b_{41}^{6c6c} \rangle = 27.38 \text{ eV}\text{\AA}^3$ is linearly interpolated for our InGaAs system between its values in GaAs and InAs [2]. Along the [110] and the $[\bar{1}\bar{1}0]$ crystallographic directions, $\beta = \langle b_{41}^{6c6c} \rangle \left(\langle k_z^2 \rangle - \frac{k_F^2}{2} \right)$, where k_F is the Fermi wavevector. Along these directions, β then decreases and turns to negative while the electronic density N_s is raised.

The devices were fabricated using electron beam lithography and electron cyclotron resonance plasma etching. The loop arrays are $200 \mu\text{m}$ long, $125 \mu\text{m}$ wide and contains approximately 4400 loops. The structure of the rectangular loops is shown in Figs. 1(c) and (d). For both KH1 and KH3, we have investigated three different geometries with a mean value of the side length $L = 1.8 \mu\text{m}$, elongation/reduction lengths $\Delta L = -0.4, 0, 0.4 \mu\text{m}$, and a channel width of $0.5 \mu\text{m}$. An 100 nm insulating layer of SiO_2 and a Au front gate were added on top of the samples in order to control N_s and the strength of the SOI. The electrical transport measurements were performed at low T in a dilution refrigerator using a standard ac lock-in technique, passing the electrical current along the [110] direction, and applying the magnetic field B perpendicular to the 2DES.

Figure 2 shows the magnetoconductance $g(B)$, corresponding to one individual loop of the array [13], measured at 300 mK for a device with $\Delta L = 0 \mu\text{m}$ and made from the KH1 wafer. The magnetotransport data show AAS oscillations, stemming from the quantum interference between closed loop trajectories propagating in clockwise (CW) and counterclockwise (CCW) directions. The general features and the V_g dependence of the measured AAS oscillations are similar to those previously reported for circular [7] and square [6, 9] loop arrays. From these data, we extract the AAS oscillations' amplitude, $-\delta g_0^{\text{AAS}}$, for each value of V_g by integrating the corresponding peak in the real part of the Fast Fourier Transform (FFT) of the magnetoconductance traces. Using this method, we keep the sign information of the AAS oscillations' amplitude and filter the higher harmonic contributions, as well as the asymmetric part of the traces [14].

Figure 3(a), that shows $-\delta g_0^{\text{AAS}}(N_s)$ for two devices with $\Delta L = \pm 0.4 \mu\text{m}$ made from the KH1 wafer, illustrates the main findings of our work. The TRAC effect shows oscillations that exhibit both different shapes and frequencies for devices with different ΔL 's. The frequency of the TRAC oscillations is found to be larger for the $\Delta L = -0.4 \mu\text{m}$ device and to decrease while ΔL is raised to $0.4 \mu\text{m}$. This result undoubtedly evidences an anisotropy of the total SOI in the 2DES. We also observe a negative, slowly varying background, whose amplitude grows with N_s , superimposed on the TRAC oscillations. Similar results were obtained for the devices made from the KH3 wafer, while the anisotropy in the TRAC oscillations and the presence of the negative background were less pronounced.

To further analyze these results, we compare $-\delta g_0^{\text{AAS}}(N_s)$ with the calculations from the SI model [8, 9] that is properly extended to account for the rectangular shape of the loops and to include both the Rashba and the Dresselhaus terms. A detailed presentation of the SI model can be found in Ref. [8, 9, 15]. Here, we briefly mention that the interference is generally examined considering the probability amplitude of linearly superposed wavefunctions. In our case, we consider the quantity $\left| \frac{1}{2}\Psi_{\text{CW}} + \frac{1}{2}\Psi_{\text{CCW}} \right|^2$, where Ψ_{CW} and Ψ_{CCW} are the wavefunctions that followed the rectangular loop in the CW and CCW directions, respectively. We note that Ψ_{CW} (Ψ_{CCW}) can be obtained by sequentially applying the spin rotation operator R (R^{-1}), resulting from the Rashba and Dresselhaus Hamiltonians, for each side of the loop, to an initial spin state Ψ_i and by multiplying by the phase factor $e^{i\phi/2}$ ($e^{-i\phi/2}$), that corresponds to the Aharonov-Bohm phase stemming from the perpendicular B . The overline in the above expression denotes an averaging of the quantity over all initial spin directions and the $1/2$ factor is used to normalize its maximum value. It

can be shown that

$$\left| \frac{1}{2}\Psi_{\text{CW}} + \frac{1}{2}\Psi_{\text{CCW}} \right|^2 \equiv A(\theta_D, \theta_R) \cos(\phi) + \frac{1}{2}. \quad (2)$$

The $\cos(\phi)$ oscillations physically correspond to the AAS effect. The oscillations in the experimental TRAC effect can be understood in terms of the SI amplitude $A(\theta_D, \theta_R)$. For our rectangular geometries, $A(\theta_D, \theta_R)$ has the following analytical form:

$$A(\theta_D, \theta_R) \equiv -\frac{1}{2} + \frac{1}{4} \left(1 + 2 \cos \theta_D \cos \theta_R - \cos^2 \theta_D \cos^2 \theta_R + \sin^2 \theta_D \sin^2 \theta_R \right)^2, \quad (3)$$

where

$$\theta_D = \frac{2m^*}{\hbar^2}(\beta L - \alpha \Delta L), \quad (4)$$

$$\theta_R = \frac{2m^*}{\hbar^2}(\alpha L - \beta \Delta L), \quad (5)$$

where $\hbar$ is the Planck constant, $m^* = 0.047 m_e$ is the electron effective mass and m_e is the free electron mass. The evolution of the SI amplitude as a function of θ_D and θ_R is illustrated in Fig. 4(a). As θ_D and θ_R depend on the SO parameters, we use one-band Poisson-Schroedinger self-consistent solutions to obtain the values of α and β as a function of N_s from the $\mathbf{k} \cdot \mathbf{p}$ formalism [2, 16, 17]. While V_g is changed, both α and β are tuned and the SI amplitude for a particular device follows a path in the $A(\theta_D, \theta_R)$ diagram. Figure 4(b) shows the probed paths in the $A(\theta_D, \theta_R)$ diagram for devices made from the KH1 wafer, with $\Delta L = 0, \pm 0.4 \mu\text{m}$ and for N_s between 1.3 and $2.8 \times 10^{16} \text{ m}^{-2}$.

The SI amplitudes $A(\theta_D, \theta_R)$ calculated from this extended SI model are further displayed in Fig. 3(b) for devices made from the KH1 wafer, with $\Delta L = \pm 0.4 \mu\text{m}$ as a function of N_s . It is worth noting that the quantum well width d_{QW} and back doping level N_1 were adjusted in the calculation to fit the experimental data. The values of d_{QW} and N_1 used in the calculations are given in the caption of Fig. 3(b), and agree well with the values used to design the pertinent heterostructures. As previously shown for square devices [6, 9], the SI model qualitatively reproduce the behaviour of the TRAC effect, *i.e.* its oscillating behaviour, as well as the shape of the oscillations as a function of N_s . In addition, for the rectangular devices investigated here, the SI model successfully reproduces the frequency evolution of the TRAC oscillations as a function ΔL . This indicates that the anisotropy of the SOI observed here is consistent with the interplay between the Rashba and Dresselhaus terms. In Fig. 4(c), we plot the SO parameters estimated from the $\mathbf{k} \cdot \mathbf{p}$ theory for the KH1 wafer. On this figure, we also show the total SOI strengths felt by electrons along the $[110]$ and the $[\bar{1}\bar{1}0]$ crystallographic directions, $\alpha + \beta$ (black dotted line) and $\alpha - \beta$ (black dashed line), respectively. The stronger N_s dependence of $\alpha + \beta$ ($[110]$) compared to $\alpha - \beta$ ($[\bar{1}\bar{1}0]$) explain the frequency decrease of the TRAC oscillations when ΔL is increased. Indeed, the longer the device's side along the $[110]$ direction, the larger the overall modification of the electrons' spin precession around the loops, while $V_g(N_s)$ is swept.

As a conclusion, we have detected the anisotropy of the SOI in InGaAs/InAlAs quantum wells using TRAC oscillations measurements in arrays of rectangular loops with their sides aligned to the $[110]$ and the $[\bar{1}\bar{1}0]$ crystallographic directions. The anisotropic TRAC oscillations, *i.e.* different frequencies for devices with different ΔL 's, were successfully reproduced using a simple SI model, indicating that the anisotropy of the SOI is consistent with the interplay of the Rashba and Dresselhaus terms.

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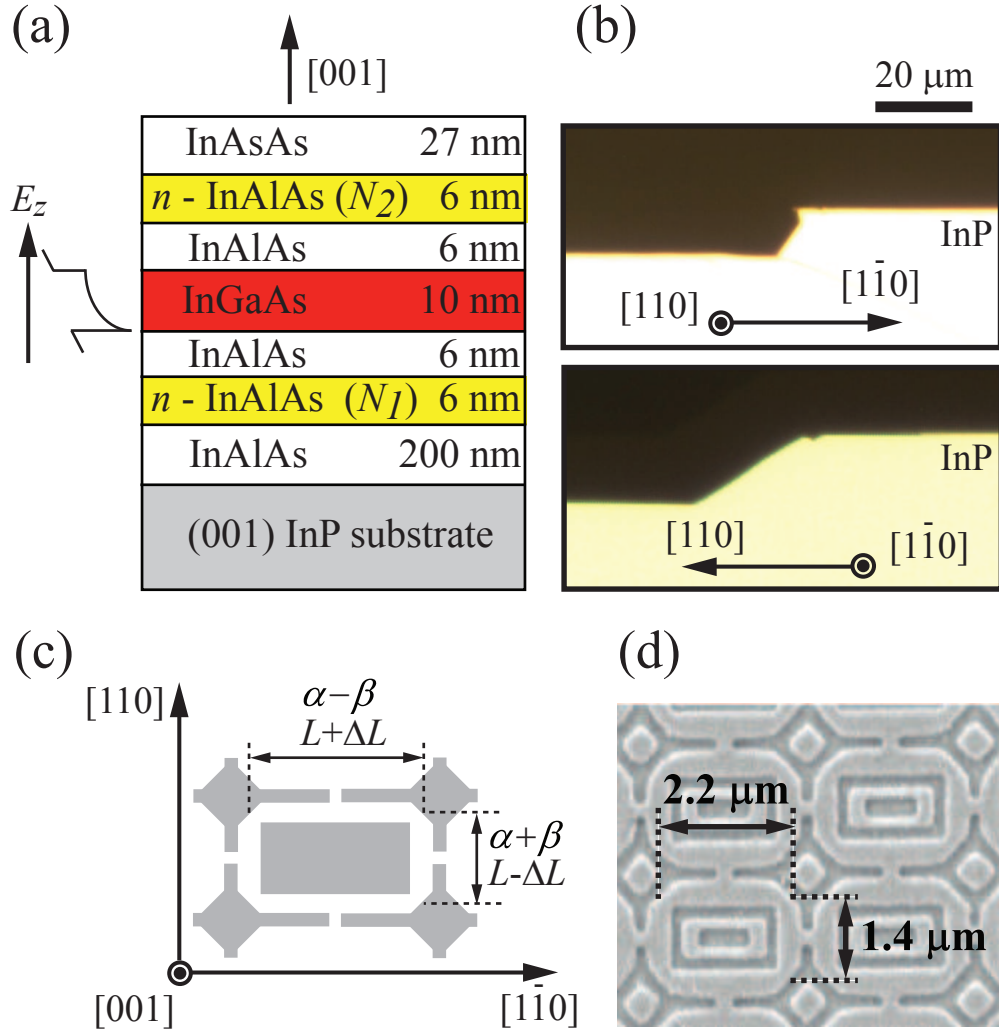


Figure 1: (color online) (a) Growth sequence of the heterostructures investigated here and schematic of the quantum well's band structure. (b) Wet etched grooves' profiles of the InP substrate (1 minute in HCl) along the [110] and $[1\bar{1}0]$ directions. (c) Schematic representation of our loops' geometries with respect to the crystal axes. (d) SEM image of a loop array with $L = 1.8 \mu\text{m}$ and $\Delta L = 0.4 \mu\text{m}$. The dark lines correspond to the etched grooves of the structure.

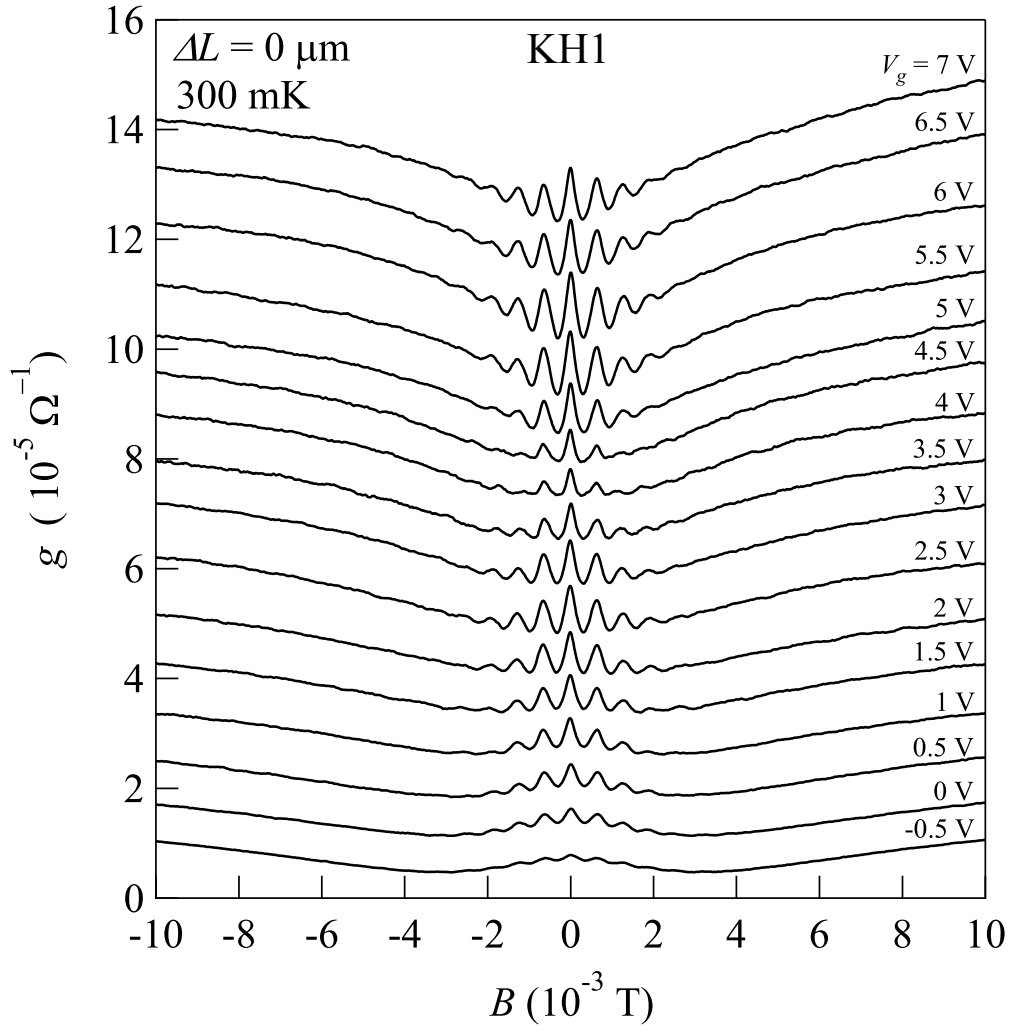


Figure 2: Magnetoconductance $g(B)$ per loop for a device with $L = 1.8 \mu\text{m}$ and $\Delta L = 0 \mu\text{m}$ at 300 mK, for various values of V_g . All traces are shifted vertically for clarity.

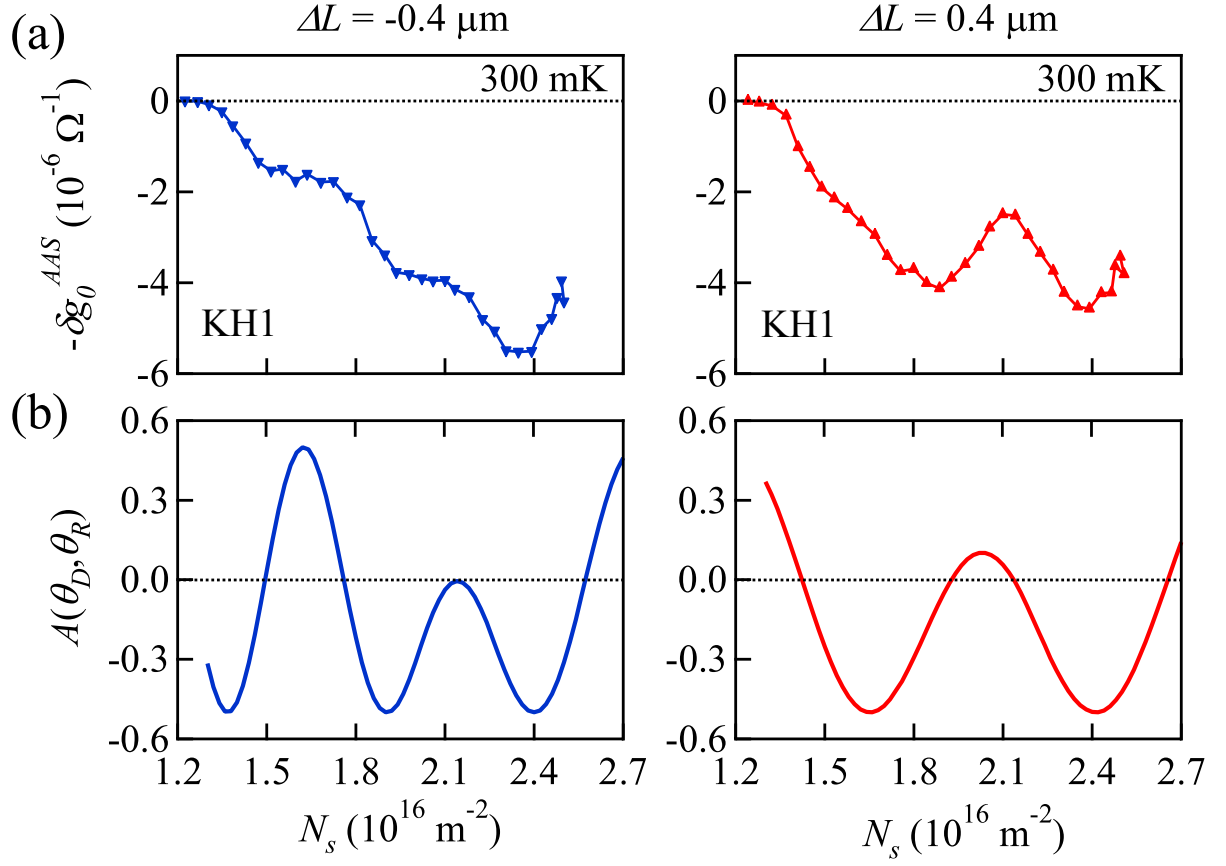


Figure 3: (color online) (a) $-\delta g_0^{AAS}(N_s)$ at 300 mK, for KH1 devices with $\Delta L = \pm 0.4 \mu\text{m}$. (b) Corresponding calculated values of $A(\theta_D, \theta_R)$ as a function of N_s , using $N_1 = 3.6 \times 10^{18} \text{ cm}^{-3}$ and $d_{QW} = 9.5 \text{ nm}$ for the devices with $\Delta L = -0.4$, and $N_1 = 3.75 \times 10^{18} \text{ cm}^{-3}$ and $d_{QW} = 9 \text{ nm}$ for the device with $\Delta L = 0.4 \mu\text{m}$.

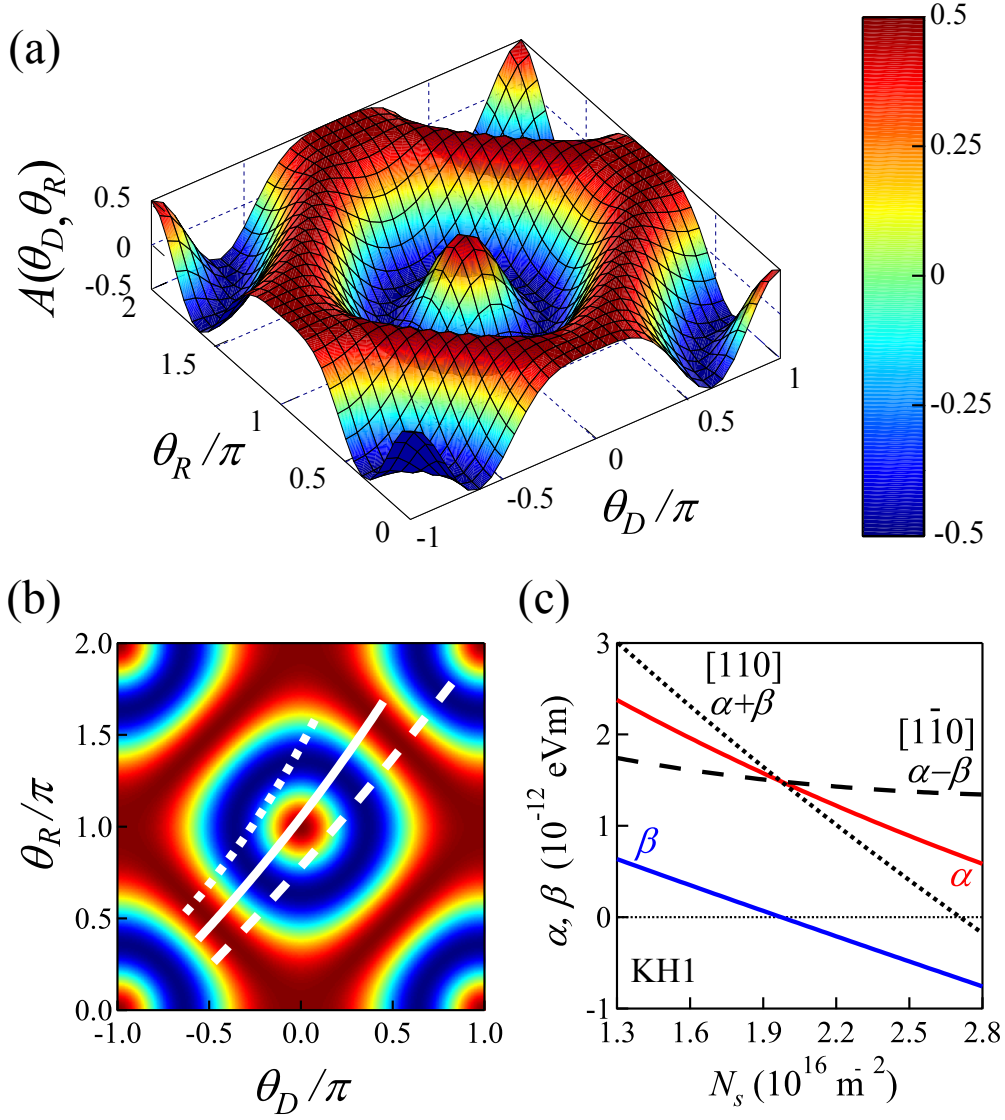


Figure 4: (color online) (a) SI amplitude $A(\theta_D, \theta_R)$. (b) Top view of the $A(\theta_D, \theta_R)$ diagram. The white lines show the paths probed in the diagram for the KH1 devices with $\Delta L = -0.4 \mu\text{m}$ (dashed line), $0 \mu\text{m}$ (plain line) and $0.4 \mu\text{m}$ (dotted line). (c) Rashba parameter α (red line) and Dresselhaus parameter, along the $[110]$ and $[1\bar{1}0]$ directions, β (blue line) as a function of N_s for the KH1 samples. The parameters α and β were calculated from the $\mathbf{k} \cdot \mathbf{p}$ theory, using $d_{QW} = 9.5 \text{ nm}$ and $N_1 = 3.6 \times 10^{18} \text{ cm}^{-3}$. The total SO strengths along the $[110]$ (black dotted line) and the $[1\bar{1}0]$ (black dashed line) crystallographic directions are also shown.