

Absorption of surface acoustic waves by a two-dimensional electron gas in the presence of spin-orbit interaction

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(Received 13 March 2003; accepted 16 June 2003)

A theoretical study is presented for interactions between surface acoustic waves (SAWs) and a two-dimensional electron gas (2DEG) in the presence of spin-orbit (SO) interaction (SOI) induced by the Rashba effect. It is found that the presence of the SOI in a 2DEG can open up new channels for electronic transitions. As a result, an enhanced absorption of the SAWs by a 2DEG can be achieved through intra- and inter-SO electronic transition around the Fermi level. These results indicate that spintronic systems can be the candidate of the SAW devices. © 2003 American Institute of Physics. [DOI: 10.1063/1.1599631]

I. INTRODUCTION

At present, one important aspect in the field of spin electronics (or spintronics) is to study spin polarized electronic systems realized from semiconductor nanostructures in the absence of an external magnetic field, due to important applications to electronic devices such as spin transistors,¹ spin waveguides,² spin filters,³ etc. It is known that in narrow-gap semiconductor quantum well structures, the presence of the heterojunctions can lead to an inversion asymmetry of the microscopic confining potential.⁴ Thus, spin degeneracy of carriers in the system can be lifted at zero-magnetic field. This effect is electrically equivalent to a nonequilibrium surface electric field and therefore is known as Rashba spin splitting.⁵ The state-of-the-art material engineering and micro- and nanofabrication techniques have made it possible to achieve experimentally observable Rashba effect in, e.g., InGaAs-based two-dimensional electron gas (2DEG) systems. Moreover, it has been demonstrated experimentally that the strength of the Rashba spin-splitting and the corresponding spin orbit interaction (SOI) in these device systems can be controlled by applying a gate voltage⁶ or varying sample growth parameters.⁷ Currently, most of the published work in this field has been focused on the influence of the SOI on electronic and transport properties of the 2DEG systems.

In this paper, we propose to study acoustic properties of a spintronic system. In recent years, there has been a rapid expansion in developing high-frequency and high-intensity ultrasonic sources such as surface acoustic waves (SAWs).⁸ Recently SAWs have been intensively used to investigate different semiconductor systems⁹ and possible device applications (such as high-speed analog signal processors,¹⁰

single-electron devices,¹¹ quantized-acoustoelectric-current devices,¹² quantum computers,¹³ etc.) have been proposed. It has been realized that when a SAW propagates in a piezoelectric material (e.g., in III-V compounds), a strong piezoelectric potential can be induced so that conducting carriers in the system can be trapped and mobilized with the SAW velocity. The influence of the SAWs on spin-transport properties has been studied very recently for a *n*-type bulk GaAs,¹⁴ which indicates that spin polarized electronic systems can interact strongly with SAWs. On the basis that a finite spin-splitting can be much more markedly achieved in InGaAs-based 2DEGs than in bulk GaAs, it is necessary and important to examine how a SAW interacts with a 2DEG in the presence of SOI and this is the prime motivation of the present study.

In this article, we will develop a simple and tractable theory to investigate the interactions between SAWs and a 2DEG when SOI induced by the Rashba effect is present. The theoretical approach to calculate the electron-energy-loss rate caused by electron interactions with SAWs will be presented in Sec. II. The numerical results will be presented and discussed in Sec. III and the conclusions drawn from this study will be summarized in Sec. IV.

II. THEORETICAL APPROACH

In the present study, we consider a 2DEG in which the SOI is induced by the Rashba effect. Including the lowest order of the SOI, the electron wavefunction and energy spectrum in the absence of a SAW can be obtained analytically by solving a Schrödinger equation.² When a SAW is launched on the surface (taken along the *x* axis) of the quantum well (the growth direction is taken along the *z* axis), the accompanied piezoelectric potential in a zinc-blende crystal can be modeled as¹⁵

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$$V_{q_x}(x, t) = V_{q_x} \exp[i(q_x x - \omega_{q_x} t)] \quad (1a)$$

with

$$V_{q_x} = \frac{8\pi e_{14} A_0}{\kappa} S_{q_x}. \quad (1b)$$

Here A_0 is the amplitude of the SAW with a wave vector q_x and a corresponding frequency $\omega_{q_x} = v_s q_x$, and v_s , κ , and e_{14} are, respectively, the longitudinal sound velocity, dielectric constant, and piezoelectric modulus of the host material. Furthermore,

$$S_{q_x} = A_1 e^{-q_x d s} + A_1^* e^{-q_x d s^*} + A_2 e^{-q_x d} \quad (1c)$$

is a sample-dependent factor, where d is a distance between the surface and the 2DEG and dimensionless coefficients $A_{1,2}$ and s are determined by the elastic constants of the host material (see the Appendix). The factor S_{q_x} is introduced in taking into account of the fact that in recent experiments, the wave vector q_x of the SAWs can be so large that the product $q_x d$ is of order unity. Thus, the steady-state electronic transition rate induced by the presence of a SAW in a spin-split 2DEG can be derived using Fermi's golden rule, which reads

$$W_{\sigma'\sigma}(\mathbf{k}', \mathbf{k}) = \frac{2\pi}{\hbar} |V_{q_x}|^2 h_{\sigma'\sigma}(\mathbf{k}, q_x) \delta_{k'_y, k_y} \delta_{k'_x, k_x + q_x} \times \delta[E_{\sigma'}(\mathbf{k}') - E_{\sigma}(\mathbf{k}) - \hbar\omega_{q_x}]. \quad (2a)$$

Here, we have considered a narrow width quantum well in which only the lowest electronic subband is present, $\sigma = \pm 1$ refers to \pm spin branches, $\mathbf{k} = (k_x, k_y)$ is the electron wave vector along the two-dimensional (2D) plane

$$h_{\sigma'\sigma}(\mathbf{k}, q_x) = \frac{1}{2} \left[1 + \frac{\sigma'\sigma(k^2 + q_x k_x)}{k[(k_x + q_x)^2 + k_y^2]^{1/2}} \right] \quad (2b)$$

is a spin-dependent element with $k = [k_x^2 + k_y^2]^{1/2}$ and

$$E_{\sigma}(\mathbf{k}) = E_{\sigma}(k) = \hbar^2 k^2 / 2m^* + \sigma\alpha k \quad (2c)$$

is the energy spectrum of the 2DEG in the presence of SOI, with m^* being the electron effective mass and α the Rashba parameter which measures the strength of the SOI. This transition rate measures the probability to scatter an electron at a state $|\sigma, \mathbf{k}\rangle$ to a state $|\sigma', \mathbf{k}'\rangle$ due to the presence of the SAWs. From Eq. (2), we see that because the piezoelectric potential induced by a SAW is along the x direction, the interaction between a 2DEG and a SAW does not alter the electron momentum (or wavevector) along the y direction and the momentum conservation law applies to electronic scattering along the x direction.

Using the electronic transition rate, the electron-energy-loss rate can be calculated by¹⁶

$$P = \frac{1}{n_e} \sum_{\sigma} \sum_{\mathbf{k}} f(E_{\sigma}(k)) \left[-\frac{d\epsilon}{dt} \right]_{\text{coll}}, \quad (3a)$$

where n_e is the total electron density of the 2DEG, $f(x)$ is the electron energy-distribution function, and

$$\left[-\frac{d\epsilon}{dt} \right]_{\text{coll}} = \sum_{\sigma'} \sum_{\mathbf{k}'} [E_{\sigma'}(\mathbf{k}') - E_{\sigma}(\mathbf{k})] W_{\sigma'\sigma}(\mathbf{k}', \mathbf{k}) \quad (3b)$$

is the variation of electron energy during a scattering event in case of a nondegenerate statistics. Thus, we obtain

$$P = \int_0^{\infty} dq_x P(\omega_{q_x}), \quad (4)$$

where

$$P(\omega_{q_x}) = \beta \frac{\hbar n_e}{4\pi^2 m^*} \hbar \omega_{q_x} \sum_{\sigma', \sigma} [I_{\sigma'\sigma}^+(\omega_{q_x}) + I_{\sigma'\sigma}^-(\omega_{q_x})] \quad (5)$$

is the energy absorption per unit time by an electron from the SAW with a frequency ω_{q_x} , which comes from all possible electronic transition channels. In Eq. (5)

$$\beta = \beta_0^2 (|S_{q_x}|^2 + |S_{-q_x}|^2) \quad (6)$$

is a dimensionless and sample-dependent parameter, where $\beta_0 = 8\pi e_{14} m^* A_0 / \kappa \hbar^2 n_e$ is a dimensionless coefficient which measures the ratio of the SAW potential amplitude to the height of the electrostatically induced potential barrier in the electronic transition channel.¹⁵ Furthermore, for the case of a low-temperature limit ($T \rightarrow 0$), we have

$$I_{\sigma'\sigma}^{\pm}(\omega_{q_x}) = \int_0^{\sqrt{4\pi n_{\sigma}}} \frac{dx \Theta(x_{\pm})}{\sqrt{(x + \sigma k_{\alpha})^2 + k_{\omega}^2}} \times \text{Re} \left[\frac{(x_{\pm} + x)^2 - q_x^2}{q_x^2 - (x_{\pm} - x)^2} \right]^{\sigma'\sigma/2}. \quad (7)$$

Here, $n_{\sigma} = (n_e/2) - (\sigma k_{\alpha}/2\pi) \sqrt{2\pi n_e - k_{\alpha}^2}$ is the electron density in the spin branch σ with $k_{\alpha} = m^* \alpha / \hbar^2$,¹⁷ $x_{\pm} = -\sigma' k_{\alpha} \pm \sqrt{(x + \sigma k_{\alpha})^2 + k_{\omega}^2}$, $k_{\omega}^2 = m^* \omega_{q_x} / \hbar$, and $\Theta(x)$ is a unit-step function.

III. NUMERICAL RESULTS

We now consider an InGaAs-based narrow quantum well structure. The effective electron mass and longitudinal sound velocity in InGaAs are, respectively, $m^* = 0.042m_e$ with m_e being the electron rest-mass and $v_s = 4.3 \times 10^5$ cm/s. We use typical sample parameters for an InGaAs-based spintronic device in our numerical calculations, such as the total electron density $n_e \sim 10^{11}$ cm⁻² and Rashba parameter $\alpha \sim 10^{-11}$ eV m.⁷ Moreover, in order to reduce the number of input parameters (such as A_0 , A_1 , A_2 , d , s , etc.) and to see more clearly the *net contributions* from electronic transitions, we scale $P(\omega_{q_x})$ the energy absorbed by an electron from the SAW with a frequency ω_{q_x} by β a dimensionless and sample-dependent parameter given by Eq. (6). It should be noted that although β is a functional form of ω_{q_x} or q_x via a factor S_{q_x} , the dependence of S_{q_x} on q_x is determined mainly by the lattice structure of the host material (see the Appendix). Hence, β does not contain any information about SOI in a 2DEG in the sample system and, as a result, $P(\omega_{q_x})/\beta$ gives net contribution induced by electronic transition events.

$P(\omega_{q_x})/\beta$ as a function of SAW frequency ω_{q_x} is shown in Fig. 1 at a fixed total electron density for different Rashba parameters. With increasing α , SOI increases and, conse-

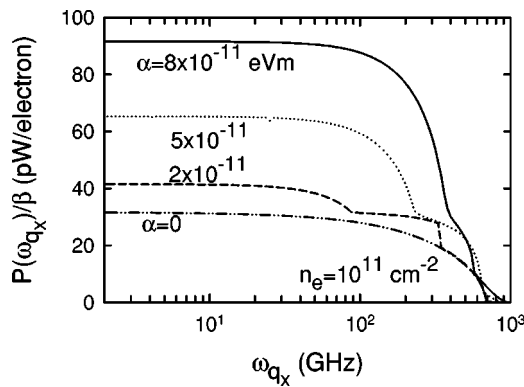


FIG. 1. Dependence of the power absorption on frequency ω_{q_x} of the SAW at a fixed total electron density n_e for different Rashba parameters α . Here β , given by Eq. (6), is a dimensionless and sample-dependent parameter and $\alpha=0$ corresponds to a case where SOI is absent. The dips shown for the case of $\alpha \neq 0$ come from inter-SO transitions (see Fig. 2).

quently, a significantly enhanced absorption of the SAW by a 2DEG can be observed via electronic transition in different spin branches. The contributions to power absorption of the SAW from different electronic transition channels are shown in Fig. 2 as a function of SAW frequency for fixed n_e and α . In the presence of SOI, more electrons are in the “-” spin branch because it has a lower energy.¹⁷ As a result, electronic transitions accompanied by the absorption of the SAW can be more possibly achieved in the “-” spin branch. From Fig. 2, we see that over a wide range of ω_{q_x} , the absorption of the SAWs is mainly caused by intra-SO transitions within the “-” branch. When high-frequency SAWs are launched to the device system, the absorption can be achieved via inter-SO transitions. Therefore, the fine structure shown in the curves of $\alpha \neq 0$ in Fig. 1, such as two dips for $\alpha = 2 \times 10^{-11}$ and 5×10^{-11} eV m, comes from contributions due to inter-SO electronic transition.

From a fundamental perspective, the SOI in a 2DEG has some unique features. (1) In the presence of SOI, the energy dispersion of a 2DEG is no longer parabolic [see, Eq. (2c)] and the energy levels of different spin branches depend strongly on k (wavevector or momentum of an electron). (2) In such a system, the spin orientation can change continu-

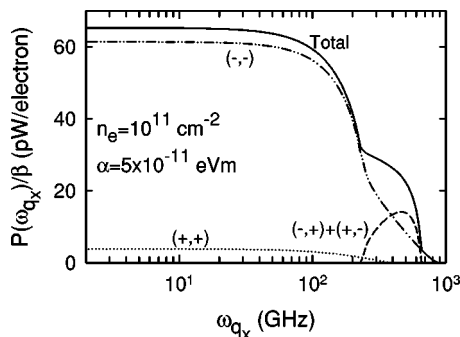


FIG. 2. Contributions to power absorption of the SAW from different transition channels as a function of SAW frequency at a fixed total electron density n_e and a fixed Rashba parameter α as indicated. Here, (σ', σ) corresponds to electronic transitions from a spin branch σ' to a branch σ and β is given by Eq. (6).

ously with the momentum orientation when an electron moves in \mathbf{k} space. As a result, the SOI can shift \pm branch of the spectrum continuously in \mathbf{k} space instead of a quantized spectrum in energy space for the usual case. (3) Most importantly, the lifting of the spin degeneracy in \mathbf{k} space opens up new channels for electronic transitions. Thus, electrons are able to change their spin orientation simply through momentum exchange which can be more easily achieved than that through energy exchange for the usual case. These features are very favorable for interacting between electrons and SAWs, and this is the main reason why an enhanced absorption of the SAW can be achieved in a system with SOI. It should be noted that at low temperatures, the power absorption of the SAW is determined mainly by electronic transitions around the Fermi level. This process requires momentum and energy conservation during an electronic scattering event. From Figs. 1 and 2, it is interesting to note that when $\omega_{q_x} < 50$ GHz, $P(\omega_{q_x})/\beta$ depends weakly on ω_{q_x} . This is because although more electronic transition events can occur to absorb relatively low-frequency SAWs, the energy gain $\hbar\omega_{q_x}$ by an electron during a scattering event is also relatively small. To absorb higher-frequency SAWs ($\omega_{q_x} > 50$ GHz), electrons have to exchange a large amount of momentum and energy, which is less possible and results in a decrease of absorption with increasing ω_{q_x} . Moreover, the requirement of the momentum and energy conservation for a scattering event implies that inter-SO transition accompanied by the absorption of SAW can only occur at relatively high SAW frequencies. It is shown in Fig. 1 that with increasing SOI, the energy separation between the \pm spin branches around the Fermi level increases and, therefore, higher-frequency SAWs can be absorbed via inter-SO transitions.

IV. CONCLUSIONS

In this article, we have demonstrated that an enhanced absorption of the SAWs can be achieved in a spin polarized 2DEG realized from a narrow-gap semiconductor quantum well. On the basis that the SOI in these systems can be altered by applying a gate voltage or varying sample growth parameters, the strength of the interaction between a SAW and a 2DEG can therefore be controlled artificially. These results indicate that spintronic systems can be used not only as novel electronic devices but also as advanced acoustic ones such as SAW devices.

ACKNOWLEDGMENTS

One of us (W.X.) is a Research Fellow of the Australian Research Council. This work was also partly supported by the National Natural Science Foundation of China and Ministry of Education, China and by the National Science Council of Taiwan under Grant No. 91-2119-M-007-004 (NCTS).

APPENDIX

For convenience in reading this article and understanding the results presented and obtained, here we summarize the results on how to calculate those coefficients shown in the factor S_{q_x} given by Eq. (1c). The theoretical approach to

calculate piezoelectric potential induced by SAWs launched on the surface of a zinc-blende crystal (such as $\text{Al}_x\text{Ga}_{1-x}\text{As}$ and $\text{In}_x\text{Ga}_{1-x}\text{As}$) has been well documented.¹⁸ According to Ref. 18, the dimensionless coefficients $A_{1,2}$ and s shown in Eq. (1c) can be calculated through

$$A_1 = \frac{\gamma - 2s}{s^2 - 1} e^{-i\phi} \quad (\text{A1})$$

and

$$A_2 = \frac{-2}{1 + \kappa} [\cos \phi + \kappa \text{Re}(A_1) + \text{Re}(sA_1)]. \quad (\text{A2})$$

Here, κ is the dielectric constant, and s is determined by solving

$$0 = (c'_{11} - Xc_{11} - s^2c_{11})(c_{44} - Xc_{11} - s^2c_{44}) + s^2(c_{12} + c_{44})^2, \quad (\text{A3})$$

γ is given by

$$\gamma = s \left[\frac{c_{12} + c_{44}}{c_{44} - (X + s^2)c_{11}} \right], \quad (\text{A4})$$

and ϕ is obtained by solving

$$e^{-2i\phi} = - \frac{\gamma^* - s^*}{\gamma - s}. \quad (\text{A5})$$

In Eqs. (A3)–(A5), c_{ij} is the elastic constant for a zinc-blende lattice, $c'_{11} = (c_{11} + c_{12} + 2c_{44})/2$, and $X = \rho v_s^2 / c_{11}$ with ρ being the density of the host material and v_s the longitudinal sound velocity. Thus, if one knows the material parameters such as c_{ij} , κ , ρ and v_s , $A_{1,2}$ and s shown in Eq. (1c) can be obtained analytically. Moreover, it has been proposed by Refs. 15 and 18 that for $\text{Al}_x\text{Ga}_{1-x}\text{As}$ -based struc-

tures, the actual values of these material parameters can be obtained by linear combination of those in GaAs and Al. On the basis that InGaAs has the same lattice structure as AlGaAs, the parameters $A_{1,2}$ and s for InGaAs-based structures can therefore be calculated by the same way used for calculating AlGaAs documented in Refs. 15 and 18.

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