SPIN LIFETIME TUNING IN ZINCBLENDE HETEROSTRUCTURES AND APPLICATIONS TO SPIN DEVICES

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ABSTRACT

We present analytical expressions for the D'yakonov-Perel' spin relaxation rates under the combined action of bulk and structural inversion asymmetry for [111] zincblende heterostructures when terms up to linear and third order in k are included in the Hamiltonian. We see for [111] heterostructures that, under the right conditions, the lowest-order-in-k component of the spin relaxation tensor can be made to vanish for *all* spin components at the same time. We study how the inclusion of terms of higher order in k affects these results. We finally discuss a proposal for a resonant spin lifetime transistor (RSLT) using the spin lifetime tuning concepts presented above, where the characteristics of the [111] device give the designer a supplementary degree of freedom on the direction of the injected spins.

1. INTRODUCTION

If the current pace of electronic device miniaturization is to continue, it is reasonable to think that the good use of the quantum properties of the electron will play a role in making this possible. Traditionally it has been the wave character of the electron that has been put to this use, resulting in devices such as the resonant tunnel diode [1] and the single electron transistor [2].

Another quantum property of the electron that only recently has received attention for its potential for information storage and processing is its spin. One of the key parameters that must be controlled for the successful achievement of *spin* elec*tronic* (spintronic) devices, such as the Datta-Das transistor [3], is the spin lifetime of the carriers. For the transport of spin-encoded quantum (single state) or classical (average over an ensemble) information, we naturally demand spin lifetimes as long as possible. If, as it is normally the case, we are to employ heterostructures in the design of our spintronic devices, we need tools that provide us with predictions about the spin lifetimes and direct us to ways of obtaining the goal of long spin lifetimes. The lack of an inversion symmetry center lifts the double degeneracy at a general **k** point in the Brillouin zone, thus greatly reducing the spin lifetime of electrons.

In this paper we investigate how the interplay of structural inversion asymmetry [4] (SIA) and bulk inversion asymmetry [5] (BIA) affects the D'yakonov-Perel'-Kachorovskiĭ [6, 7] spin lifetimes for electrons in [111] quantum wells (QWs). The effects of SIA on the spin dynamics should always be kept in mind, as it can be unintentionally present in any heterostructure due to uneven doping profiles [8], surface effects, different interdiffusion at the boundaries, etc. We start, in Sec. 2, by computing the effective spin Hamiltonian in a two-band model. In Sec. 3 we then proceed to compute the ensemble lifetime of the three spin components as a function of the relative magnitude of BIA and SIA contributions following the procedure from Refs. [9] and [10]. Finally, in Sec. 4 we review a newly proposed family of devices [11, 12] based on the special properties of the spin lifetime tensor when the BIA and SIA effects have equal strength in a [001] QW, as pointed out by Averkiev and Golub [13], and Kiselev and Kim [14]. The same kind of devices has also been proposed in [110] structures by Hall *et al.* [15]. We show how [111] versions of the device are expected to have properties that make them easier to implement than their [001] and [110] counterparts.

2. TWO-BAND HAMILTONIANS

Here we present the effective two-band [spin-resolved conduction band (CB)] Hamiltonian corresponding to zincblende [111] QWs. We start from the $\mathcal{O}(k^3)$ spin part of the Hamiltonian for bulk zincblendes [6]

$$H_{\mathrm{BIA}} = \gamma \left[\sigma_x k_x \left(k_y^2 - k_z^2\right) + c.p.\right], \tag{1}$$

where σ_i are the Pauli matrices, k_i are the electron wavevector components and $c.p.$ stands for the cyclic permutation needed to obtain the remaining terms of the Hamiltonian.

We first do a change of basis to express H_{BIA} in natural coordinates for the [111]-grown structures. Then, following the procedure in Refs. [7] and [16], we quantize $\mathbf{k}$ along the growth direction and, keeping only terms linear in $\mathbf{k}_{\|}$—second order terms in $\mathbf{k}_{\|}$ vanish because of time reversal requirements for the expectation value of k_z [16]—, we arrive at the following expressions for the BIA Hamiltonian of [111] QWs

$$H_{\mathrm{BIA}\,[111]} = \frac{2\gamma\langle \hat{k}_z^2\rangle}{\sqrt{3}} \left(k_y\sigma_x - k_x\sigma_y\right), \tag{2}$$

where the labels x, y, z depend on the orientation of the structure.

Upon inspection of the Hamiltonian in Eq. (2) we see that BIA causes a $\mathbf{k}$-dependent effective magnetic field pointing in-plane for [111] structures. Note that $H_{\mathrm{BIA}\,[111]}$ is formally identical to the Rashba Hamiltonian [4]

$$H_{\mathrm{R}} = \alpha_{\mathrm{R}} \left(k_y\sigma_x - k_x\sigma_y\right), \tag{3}$$

where α_{R} is the Rashba coefficient, whose value depends on the particulars of the structural asymmetry present in the sample. We shall now see that this has important consequences in the values of the spin lifetimes.

3. SPIN LIFETIMES

Here we follow the methods of Averkiev and Golub [10, 13] to compute the spin lifetime of electrons in the CB of [111] QWs. The results presented are explained in more detail in Ref. [17].

The combination of Eqs. (2) and (3) yields the first order Hamiltonian

$$\begin{aligned} H_{\mathrm{IA},1} &= \left(\alpha_{\mathrm{BIA}} + \alpha_{\mathrm{R}}\right)\left(k_y\sigma_x - k_x\sigma_y\right) \\ &= \alpha_{\mathrm{IA}}\left(k_y\sigma_x - k_x\sigma_y\right), \end{aligned} \tag{4}$$

where $\alpha_{\mathrm{BIA}} \equiv 2\gamma\langle \hat{k}_z^2\rangle/\sqrt{3}$ and we have introduced $\alpha_{\mathrm{IA}} = \alpha_{\mathrm{BIA}} + \alpha_{\mathrm{R}}$ describing the combined effects of BIA and SIA in the heterostructure.

Since Eq. (4) is formally identical to the Rashba Hamiltonian, the existing results for SIA only [10, 13] will hold taking $\alpha_{\mathrm{R}} \to \alpha_{\mathrm{IA}}$:

$$\tilde{\tau}_x = \tilde{\tau}_y = 2\tilde{\tau}_z = \frac{\hbar^2}{2\alpha_{\mathrm{IA}}^2}\frac{1}{k^2\tilde{\tau}_1}, \tag{5}$$

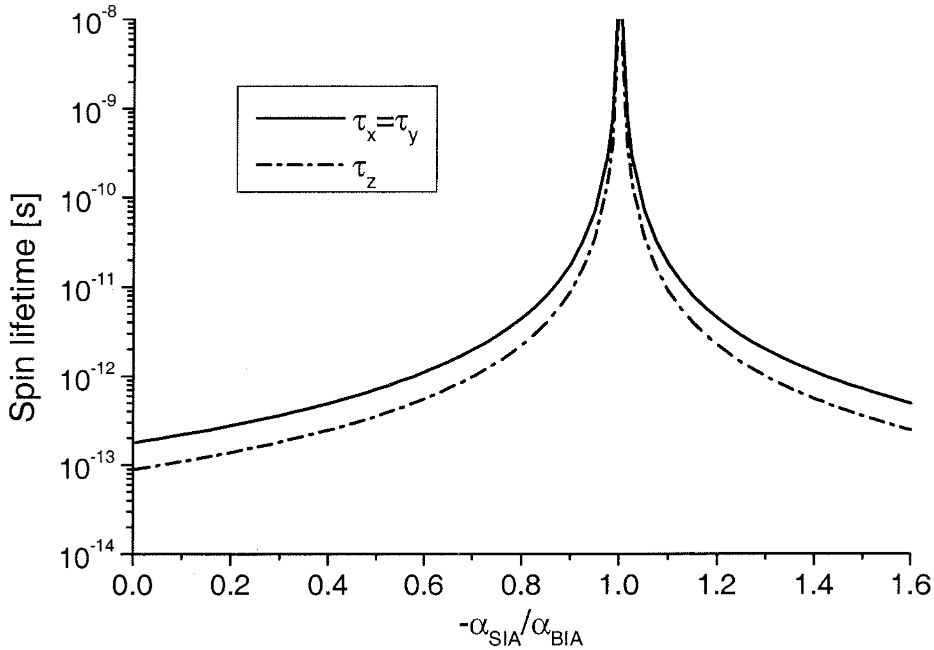

Figure 1: Spin lifetimes for the three spin components for a [111]-grown QW (upper panel) and a [110]-grown QW (lower panel) as a function of the ratio of the SIA and the BIA parameters.

where the tilde indicates a magnitude that is evaluated at a given energy and $\tilde{\tau}_1$ is the effective time for field reversal due to the harmonic $l = 1$ of the scattering cross section, and in general [10, 18] $\tilde{\tau}_l^{-1}(E) = \oint \sigma(\phi, E)(1 - \cos l\phi)d\phi$. The spin directions will be perpendicular to the wavevector and in-plane [19, 20]. We see that, as usual in the D'yakonov-Perel (DP) mechanism, the spin lifetime is inversely proportional to the momentum lifetime.

A most interesting configuration for [111]-grown samples occurs when $\alpha_{\text{BIA}} = -\alpha_{\text{R}}$. Then, $\alpha_{\text{IA}} = 0$ and the conduction bands become spin degenerate to first order in $\mathbf{k}$. The most significant consequence of this configuration would be that the spin lifetimes would be extended for *any* spin direction, as opposed to spins along [110] for (100) structures and $\alpha_{\text{BIA}} = \alpha_{\text{R}}$ [13] or spins perpendicular to the plane well for (110) structures and $\alpha_{\text{SIA}} = 0$ [7]. Control of α_{R} can be achieved by the application of a gate bias [19, 21] or by sample design with compositional asymmetry, providing a nonzero α_{R} at zero bias. Thus, properly biased (111) QWs could act as spin reservoirs, or form the basis of a resonant spin lifetime transistor as described below.

If we include terms of order in k^3 in the Hamiltonian, we obtain the following results for the spin lifetimes [17]

$$\tilde{\tau}_x = \tilde{\tau}_y = \frac{6\hbar^2}{k^2\tilde{\tau}_1} \frac{1}{12\alpha_{\text{IA}}^2 - 4\sqrt{3}\gamma\alpha_{\text{IA}}k^2 + (1 + 2\tilde{\tau}_3/\tilde{\tau}_1)\gamma^2 k^4}$$
$$\tilde{\tau}_z = \frac{3\hbar^2}{k^2\tilde{\tau}_1} \frac{1}{\left(\gamma k^2 - 2\sqrt{3}\alpha_{\text{IA}}\right)^2}. \tag{6}$$

Since the scattering rate is proportional to $(H_{\text{IA}})^2$, the k^6 terms in Eq. (6) are not correct in general because terms arising from the combination of $H_{\text{IA},1}$ with fifth order contributions to H_{IA} are missing. However, we have kept the k^6 terms here because they are correct in the special case where $\alpha_{\text{IA}} = 0$, giving the lowest order contribution to the spin scattering rate.

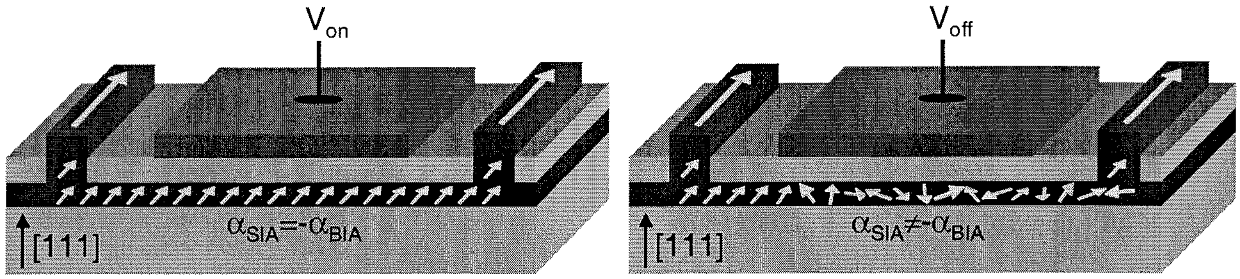

Figure 2: Operating principle of the resonant spin lifetime transistor. The gate bias drives the lifetime of the injected spins on- or off-resonance. In the "on" state the spins would arrive aligned with the ferromagnetic collector, thus resulting in low resistance. In the "off" state, the spins are randomized before reaching the collector and a high resistance is measured.

Equation (6) is plot in Fig. 1 for typical values $k_F = 0.01$ Å^{-1}, $\tau_p = 1$ ps, $\gamma = 186$ eV·Å^3 [22], $\alpha_{\mathrm{BIA}} = 11 \times 10^{-10}$ eV·cm [23] as a function of the ratio $\alpha_{\mathrm{R}}/\alpha_{\mathrm{BIA}}$. The τ_x, τ_y and τ_z components show the predicted resonant spin lifetime when $\alpha_{\mathrm{R}} = -\alpha_{\mathrm{BIA}}$. Although Eq. (6) limits by itself the values of the lifetimes at the resonance, these values are very large and, thus, other mechanisms [24–26] will effectively limit the value of the resonant spin lifetime. Therefore, [111]-grown heterostructures provide DP suppression on par with [110]-grown structures, with the added advantage the suppression is for *all* spin components, as opposed to one component only.

4. DEVICES

In what follows, we will describe how, by driving the spin lifetime in and out of resonance through the action of an external bias, we can construct a series of spintronic devices. Figure 2 shows the operating principle of the [111] resonant spin lifetime transistor (RSLT). The device layout is very similar to the Datta-Das [3] device. As opposed to the [001] ([110]) version of the device, where the ferromagnetic contacts must be designed so that their magnetization points in the $[\bar{1}10]$ ([110]) direction, the fact that all spin components are resonant at the same time gives the designer freedom to choose the orientation of the magnetization. Thus, we can choose to have the magnetization in-plane as normally obtained from the demagnetizing fields.

Another advantage that must be pointed out for [111] heterostructures is that, because of the form of Eq. (2), BIA effects will give a constant background to the Rashba Hamiltonian, and therefore will not disturb, to first order, the operation of the Datta-Das transistor.

At first, an ensemble of spins is injected in the 2DEG. The gate bias drives the lifetime of the injected spins on- or off-resonance by setting $\alpha_{\mathrm{BIA}} = -\alpha_{\mathrm{SIA}}$ or $\alpha_{\mathrm{BIA}} \neq -\alpha_{\mathrm{SIA}}$, respectively. In the "on" state the spins would arrive aligned with the ferromagnetic collector, thus resulting in low resistance. In the "off" state, the spins are randomized before reaching the collector and a high resistance is measured.

There are other kinds of devices that can be constructed with these building blocks. If the gate bias in Fig. 2 is applied through a charged/uncharged floating gate, the device would behave as a flash memory. A different nonvolatile memory configuration can be obtained from Fig. 2 if the gate bias is always kept at the resonance condition. Then, the "0" or "1" states would be given by the relative orientation of the magnetization of the emitter and the collector. The performance would improve because this memory can operate in the ballistic mode. We can also envision a magnetic information readout head based on this last nonvolatile memory. Similar to giant magnetoresistance readout heads [27], the magnetization of one contact would be pinned while the other follows some stored pattern. Finally, strain effects are likely to also distort the spin lifetime of the electrons, which might lead to spintronic strain gauges.

5. SUMMARY

In summary, we have shown that electrons in the conduction band of a [111] zincblende quantum well have extended spin lifetimes for *all* spin components when BIA and SIA effects are of equal magnitude. This effect can be used to improve on the resonant spin lifetime transistor, where a gate bias modulates the resistance of a channel through the spin lifetime of a 2DEG. The [111] version of the device is free from constraints in the transport direction crystallographic orientation does not need to specify the orientation of the magnetization of the contacts. Also, the the DP

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