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Prediction of Spin-Polarization Effects in Quantum Wire Transport

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We predict new spin polarization effects in thin quantum wire transport. We show, that electron-pair scattering for electrons in the two spin subbands of a thin quantum wire can be dramatically different and we show the construction principle of an active spin polarizer based on this effect. Hot electrons in one subband (e.g. 'spin up') pass such a device with weak electron pair scattering, while electrons in the opposite subband (e.g. 'spin-down'), have high conversion probability into the 'spin-up' subband, resulting in spin polarization of a hot electron beam. In a differently constructed device, a hot electron beam passing through a single mode quantum wire may induce a steady state magnetization of the background electron gas in a section of a quantum wire.

Transport in electron wave guides, quantum wires and quantum dots is presently an active area of research (for a review see Ref. [1]). Research on growth methods and properties of quantum wires is motivated by one or more of the following aims or predictions:

- to make low threshold quantum wire lasers
- to achieve very high mobility transport in quantum wires due to reduced scattering
- crystal growth challenge—refinement of crystal growth techniques
- verification of new electronic ground state in a quantum wire (e.g. prediction of Luttinger liquid, charge density wave state ...)
- to understand transport effects in small 'mesoscopic' electronic structures

In the present work, we add new predictions as possible aims for quantum wire research: we predict two related new effects [2], achievable in devices based on single mode quantum wires with spin splitting of the electron bands: (1) a quantum wire structure, acting as an active spin polarizer for hot electrons, and (2) a device structure where a beam of hot electrons induces a steady state magnetization of the background electron gas in a section of the quantum wire. These effects will allow the construction of several new devices and experiments.

The basic principle of spin subband dependent pair scattering rates is demonstrated in Fig. 1. Even in a 'single mode' quantum wire (i.e. in a quantum wire of approx. $50nm$ thickness with only one conduction subband contributing), the conduction band has two spin subbands. In general, these two bands do not have the same energy and show spin splitting. This splitting has been investigated theoretically [3] [4] [5] and experimentally [6] [7] [8] in 3D and in 2D and is of the order of $1meV$ at the Fermi edge under typical conditions.

In Fig. 1 we look at pair scattering of **(a)** an electron with wave vector $\mathbf{p}_1$ in the spin-up band and **(b)** of an electron at $\mathbf{p}_2$ in the spin-down band. For each case we show a typical pair scattering process with a partner electron near the Fermi surface. Once the electron at $\mathbf{p}_1$ or $\mathbf{p}_2$ and the partner electron at $\mathbf{k}_1$ and $\mathbf{k}_2$ have been chosen, energy and momentum conservation together with the band dispersion fix the final states. (For the purpose of producing Fig. 1 we have calculated the final states from a realistic dispersion relation using the 'Mathematica' software). The scattering process shown in Fig. 1(b) has much higher probability than the process in Fig. 1(a), since the Fermi population factors will be much more favorable for scattering. ($\mathbf{p}_1 + \mathbf{q}_1$ in **(a)** has a high probability of being occupied, reducing the scattering probability of the process in Fig. 1(a) dramatically compared to **(b)**). Therefore, an electron injected into the 'spin-up' subband is likely to pass the quantum wire with low scattering probability. An electron

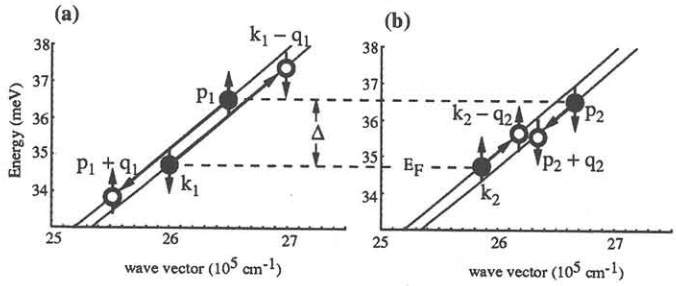

Figure 1: *Spin-subband dependence of electron pair scattering:* **(a)** *Electron in the 'spin-up' band with wave vector* $\mathbf{p}_1$ *has lower scattering rate since intermediate state at* $\mathbf{p}_1 + \mathbf{q}_1$ *has high probability to be filled.* **(b)** *Scattering rate for electron* $\mathbf{p}_2$ *in the 'spin-down' band is much higher, since the final state* $\mathbf{k}_2 - \mathbf{q}_2$ *has lower thermal occupation probability than the final state in (a) at* $\mathbf{p}_1 + \mathbf{q}_1$*. Pair scattering is only allowed with a partner electron of opposite spin (even in 2D scattering for electron pairs of equal spin is reduced [9]).*

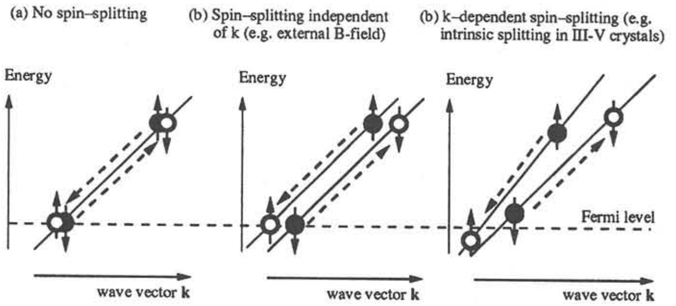

Figure 2: **(a)** *Electron pair scattering in the conduction band of a thin quantum wire without spin splitting,* **(b)** *in conduction band with wave vector independent spin splitting.* **(c)** *k-dependence of the spin splitting makes the pair scattering asymmetric with respect to spin subbands.*

$(\mathbf{p}_2, \downarrow)$ injected into the 'spin-down' subband, on the other hand, has an increased scattering probability as demonstrated in Fig. 1(b). There is a high probability that an injected electron in the 'spin-down' subband is converted into a hot 'spin-up' subband electron at similar energy. Therefore the quantum wire can act as an active electron polarizer.

Fig. 2 shows that the spin subband dependence of electron pair scattering is a result of the $\mathbf{k}$-dependence of the spin splittings. To demonstrate the spin subband dependence of pair scattering we have calculated the differential pair scattering rates as a function of wave vector $\mathbf{k}$ of the partner electron, and as a function of excess electronic energy Δ. The details of the calculations are explained in [2]. Fig. 3 shows typical

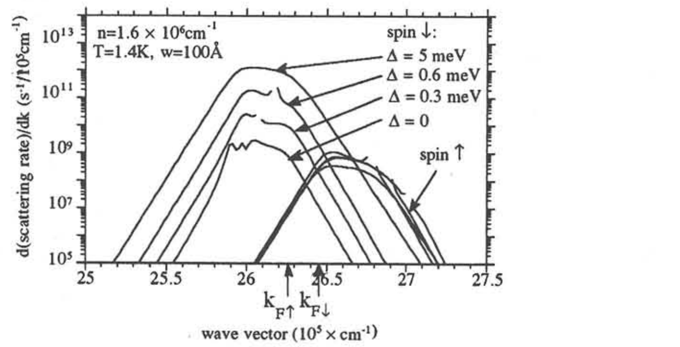

Figure 3: *For hot electrons* ($\Delta > 0$) *and scattering with partners on the 'near-side' of the Fermi surface, the electron pair scattering rate may be orders of magnitude larger for one particular spin orientation (here spin-down) than for the opposite orientation. This effect is mainly due to the Fermi population factors and the Pauli principle. (Irregularities and divergences in the curves occur for scattering vectors extremely close to* $\mathbf{q} = 0$ *and are partially eliminated from the Figure, they are not eliminated for the final integrations of total scattering rates however. Scattering at* $\mathbf{q} = 0$ *is believed not to break the electron phase.)*

results of the calculation, and demonstrates that the pair scattering rates can be many orders of magnitude different for the two spin subbands. As explained in [2], the total scattering rates are the balance of scattering with partner electrons at the 'near side' and the 'far side' of the Fermi surface. The spin subband dependence is expected to be strongest for hot electrons, i.e. for electrons some energy Δ above the Fermi energy.

Fig. 4 demonstrates schematically the construction of a quantum wire spin polarizer based on spin subband dependent pair scattering rates. The wire length has to be less than the scattering length for 'spin-up' electrons (using the convention of the present Letter), less than the probability for scattering with partners near $\mathbf{k} \approx -\mathbf{k}_F$ and longer than the scattering rate for electrons in the 'spin-down' subband. Calculation shows that this can be fulfilled in $GaAs/Al_xGa_{1-x}As$ based quantum wires, for excess energies Δ of the order of $5meV$, operating temperatures of $T = 4K$ or below, and wire lengths in the μm-range. Acoustic phonon scattering is expected to be weaker than electron scattering effects up to at least $100K$, while

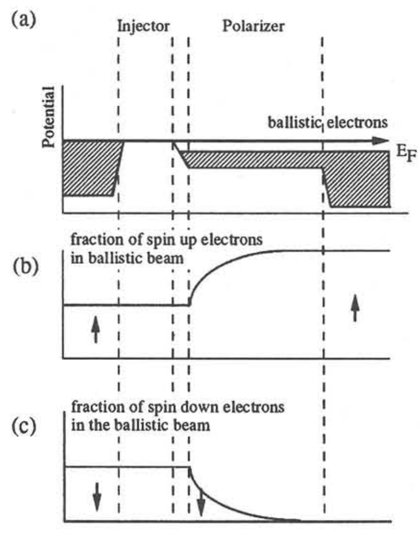

Figure 4: **(a)** *Schematic design of a quantum wire spin polarizer for hot electrons.* **(b)** *and* **(c)** *show the fraction of electrons in the 'spin-up' and in the 'spin-down' subbands in the hot electron beam. In this case the background electron gas in the wire is coupled to the a thermal bath which equilibrates the spin distribution*

we expect that optical phonon scattering will destroy this effect above approximately $100K$. Sufficiently high mobility is required, so that impurity and roughness scattering are lower than electron-electron scattering. Since in-built microscopic electric fields affect the spin-splitting of the quantum wire, and since interface roughness can affect microscopic electric fields, it could also negatively affect the spin polarization phenomena. Plasmon scattering is a possible loss mechanism reducing efficiency and is neglected here. So far we have assumed that the background electron gas in the wire is sufficiently coupled to the environment, so that its distribution is not disturbed by the injected electron beam. The opposite limit is the case of weak coupling of the background electrons in a section of the wire to the surroundings, as demonstrated in Fig. 5. In this case the injected electron beam will flip background electrons between spin subbands with unequal probability, leading to unequal spin populations and a steady state magnetization of the background electrons.

In summary, we have shown that spin splitting causes spin subband dependent electron pair scattering rates. Using this effect, an active electron spin polarizer can be constructed from a quantum wire. We have calculated the spin dependent differential electron pair scattering rates as a function of electron excess energy. We have introduced a further related effect: a hot electron beam can induce spin polarization (corresponding to a steady state magnetization) in a section of a quantum wire, which is weakly coupled to the surroundings. This work opens the possibility of a range of spin dependent experiments in microelectronic structures.

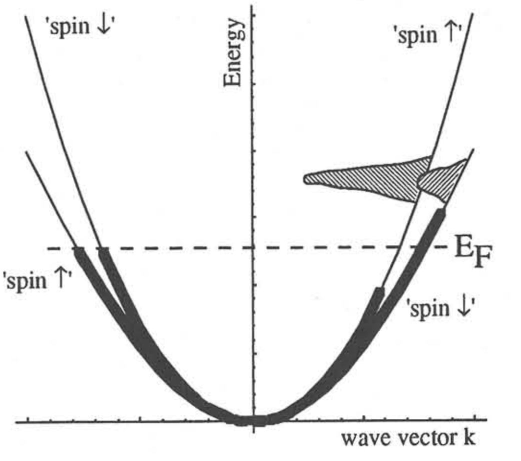

Figure 5: *Schematic diagram showing a spin polarization of the electron gas in a quantum wire with spin splitting, induced by a hot electron beam due to spin subband dependent electron scattering rates.*

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