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Confinement-Enhanced Valley Splitting for Spin-Driven Silicon Devices

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With MOSFET scaling apparently approaching its fundamental limits, the semiconductor industry is facing critical challenges, calling for new engineering solutions and innovative techniques in order to improve CMOS device performance. At the same time the research of possible device concepts for a post-CMOS era has intensified. Spin attracts increasing attention as a degree of freedom for future nanoelectronic devices. Spin-controlled qubits may be thought of as a basis for upcoming logic gates. It is important that the new devices maintain their integrability with CMOS technology. Silicon as the main element of microelectronics possesses several properties making it attractive for spintronics applications. Silicon is composed of nuclei with predominantly zero spin thus possessing a negligible degree of spin decoherence due to hyperfine interaction. Silicon is also characterized by a weak spin-orbit interaction making spin-relaxation mechanisms relatively inefficient [1]. In a recent experiment a coherent spin propagation through a 350 µm thick undoped silicon wafer was demonstrated at about 80K [2].. Spin coherent propagation at such long distances makes the fabrication of spin-based switching devices likely already in the near future.

However, the conduction band of silicon consists of six degenerate valleys. Their quantum numbers may therefore interfere with the spin degree of freedom. For successful application of silicon devices for spintronics the degeneracy between the valleys must be removed and made larger than the spin Zeeman splitting. In thin silicon films of Si/SiGe heterostructures the six fold degeneracy is partly lifted due to biaxial strain and subband quantization. There exists a controversy about the value of energy splitting between the two ladders of unprimed subbands. Shubnikov-de-Haas measurements in an electron system composed of thin silicon films in Si-SiGe heterostructures reveal that the valley splitting is in micro-volts [3], which is much smaller than theoretical estimates [4]. This small value of valley splitting is attributed to a slight misalignment of the Si/SiGe interface from the (001) direction, when the valley splitting gets exponentially suppressed [3,4,5,6] At the same time recent experiments on the conductivity measurements of point contacts performed by confining a quasi-two-dimensional electron system in lateral direction with the help of additional gates deposited on the top of the silicon film demonstrate a splitting between the remaining valleys larger than the spin splitting [3].

In this work we demonstrate that a large valley splitting in a point contact is due to an additional lateral confinement. Our analysis is based on the Hensel-Hasegawa-Nakayama **k·p** model for the conduction band in silicon [7]. Our **k·p** model including strain is accurate up to energies of 0.5eV, therefore, it can be used to describe the subband structure in thin silicon films and nanowires, where the subband quantization energy may reach a hundred meV.

Fig.1 shows the dispersion of the two lowest subbands with the same quantum number n = 1 in a (001) silicon film of thickness 3.5nm. The subbands are degenerate at the point **k**=0. The energy dispersions of the subbands with the same quantum number coincide along the [100]/[[010] direction, while the dispersions are different in the [110]/[-110] direction. The dependence of the effective masses on the film thickness calculated along the [110]/[-110] directions for the two lowest subbands from Fig.1 is shown in Fig.2. The subbands are, however, nonparabolic as demonstrated in Fig.3.

The same dispersion along the [100]/[010] direction and the different dispersion (effective masses) in the [110]/[-110] direction indicate that the structure of one-dimensional (1D) subbands in a point contact depends on its orientation: if the point contact is created along the [100] direction, the 1D subband remain degenerate, while a substantial splitting should be observed in [110] point contacts. Fig4. and Fig.5 confirm these expectations indeed, where the dispersions of 1D subbands in a differently oriented nanowires are shown. Fig.6 explains a possibility of the valley splitting enhancement by an additional lateral electrostatic confinement in a [110] point contact. All these results demonstrate the feasibility of silicon based devices operating with spin.

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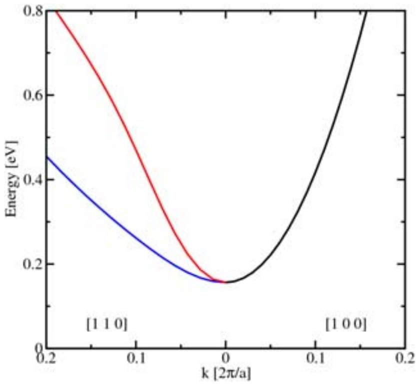

Fig.1 Energy dispersion of the four lowest subbands in a (001) Si film of 1.6nm film thickness. The dispersions are not equivalent along [110] direction.

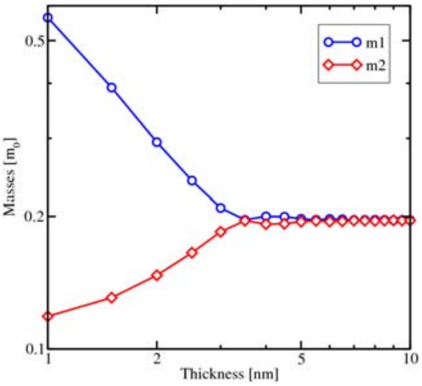

Fig.2 Curvature effective mass dependence on film thickness along [110] direction for the two ground subbands shown in Fig.1.

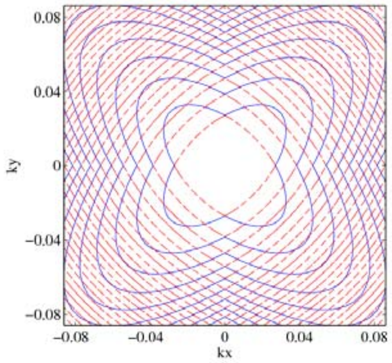

Fig.3 Dispersions of the two ground subbands for a film thickness of 1.36nm.

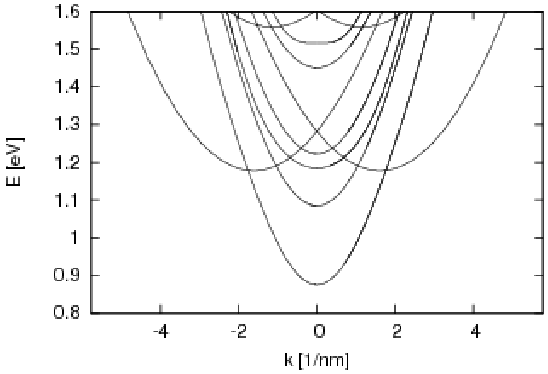

Fig.4 Subband structure in a [001] oriented fin of a 3x2nm^2 cross section, with (100) and (010) faces. The 1D ground subband is 2-fold degenerate.

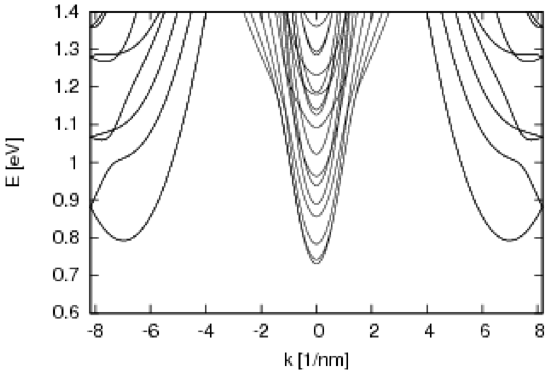

Fig.5 1D subbands in a [110] oriented fin of 3nm (001) faced width and 2nm (-110) facedd height. The degeneracy of the n=1 subband is lifted.

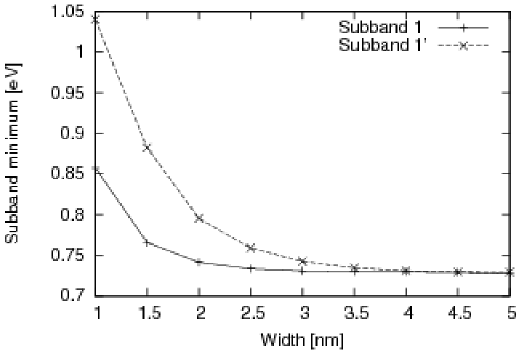

Fig.6 Dependence of the subband minima on the width of a point contact. The height is 2nm. The splitting between the ground subbands is controlled by the confinement.