Potential Fluctuations in SiGe Quantum Wells

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We are able detect the electron spin resonance due to free carriers in modulation doped SiGe/Si/SiGe quantum wells due to its exceedingly small line width of down to 0.03 G. From the ESR we obtain the density of states that allows us to evaluate potential fluctuations and the Thomas-Fermi screening efficiency. The length scale of the fluctuations is estimated from the hyperfine broadening of the ESR. It implies ionized donors in the doping layer as the main source of fluctuations.

1. Introduction

Two-dimensional SiGe structures with particular design exhibit higher mobility than bulk crystals and therefore they allow the construction of devices with higher limiting frequency than Si. The mobilities obtained, however, and thus the maximum frequency, are still below the theoretical limit and therefore it is important to know the limiting processes. In this project, we investigate potential fluctuations in the two-dimensional (2D) channel of a SiGe/Si/SiGe structure by means of electron spin resonance (ESR). We show that these fluctuations limit the electron mobility.

Modulation doped quantum wells of Si embedded between SiGe barriers exhibit in standard X-band ESR an extremely sharp resonance [1] – [3] with a g-factor close to 2.0000. The line width under optimum conditions is 30 mG, *i.e.*, two orders of magnitude narrower than that of donors in Si. We identified this resonance as that of the free carriers in the quantum well on behalf of its two-dimensional symmetry, its scaling with the carrier density and its persistent properties after illumination [2].

In this paper we describe the determination of the magnetic susceptibility of the 2D electron gas (2DEG) from ESR and its evaluation in terms of the Pauli susceptibility. The latter is proportional to the density of states (DOS) of the 2DEG which, for an ideal system, should be constant above the band edge. We observe rather a smooth onset which we attribute to the existence of fluctuations. The Thomas-Fermi screening efficiency is also proportional to the density of states [4], and it is determined thus in the same experiment. Using this quantity we calculate the mobility, and we obtain good agreement with experimental data. This demonstrates that potential fluctuations which are responsible for the band tails are also responsible for the limited mobility. From the ESR line width we derive an average length scale for the fluctuations of the order of 1 µm. Such smooth fluctuations can arise only from remote ionized impurities.

2. Experimental

Modulation doped $Si_{0.75}Ge_{0.25}$/Si quantum wells were grown pseudomorphically on top of a linearly graded, relaxed $Si_{0.75}Ge_{0.25}$ buffer by MBE. To achieve n-type conductivity, an Sb-doped layer (25 nm thick) was placed 12 nm above the quantum well. After cooling in darkness, samples with a volume doping concentration of 7.10^{17} cm^{-3} are insulating. Prolonged illumination increases the electron concentration to 3.10^{11} cm^{-2} and a mobility exceeding 10^5 cm^2/Vs at 4.2 K. For gated samples, a Pd layer was evaporated in order to allow control of the 2DEG density.

Measurements were performed with a standard Bruker X-band spectrometer. We observe a strong increase of the integral CESR absorption with increasing illumination dose after cooling in darkness, and finally for prolonged illumination, the signal saturates. For a gated sample, we see a rather weak signal for zero bias that increases for accumulation and it saturates also for higher positive bias voltage.

In order to determine the carrier concentration *in situ*, we make use of cyclotron resonance (CR) which causes a broad background signal [2] in the standard ESR experiment. The CR amplitude increases and at the same time the CR width decreases persistently with increasing illumination dose. The latter reflects momentum scattering indicating improved mobility as the Fermi level moves up and away from the tail states. The CR signal can be fitted using the Drude expression for the dielectric function taking both the CR-active and the CR-inactive parts into account as it is necessary since linear polarized microwaves are used in our experiments [2]. The carrier concentration is normalized to its saturation value. The latter was determined independently by investigating Shubnikov - de Haas oscillations.

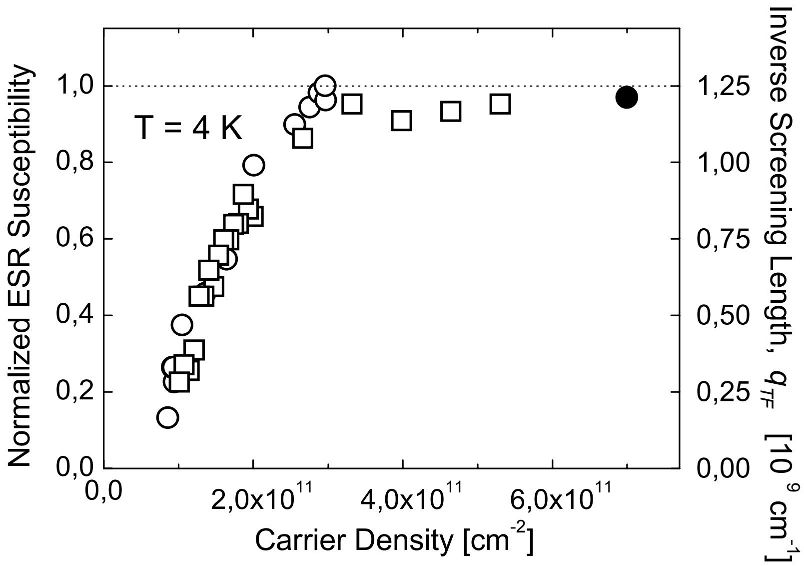

Fig.1: Normalized ESR susceptibility of the 2DEG as a function of carrier density for an ungated sample (circles), the same sample with a gate electrode (squares) and a highly doped sample (dot). The rhs scale gives the value of the Thomas-Fermi screening vector.

For gated samples, we used C-V measurements to determine the carrier density.

The integral ESR absorption is proportional to the magnetic susceptibility. In order to evaluate the DOS quantitatively we normalized the integral CESR signal to its saturation value and we assigned the unperturbed 2D DOS to that value. Typical results for the DOS at the Fermi level, $g(\varepsilon_F)$, are given in Fig. 1 as a function of the 2DEG density. The results show a smooth increase in the density of states instead of the sharp jump expected for an ideal 2DEG. For n_s, it approaches the ideal constant value asymptotically. For an ideal 2D DOS, the saturation carrier density of $n_s \approx 3.10^{11}$ cm^{-2} corresponds to a Fermi energy of about 2 meV above the unperturbed band edge.

Within the Thomas-Fermi model, the screening efficiency q_{TF} (inverse screening length) is also proportional to the density of states at the Fermi level, $g(\varepsilon_F)$ [4]. We are thus able to add another scale to Fig.1 giving that quantity. Both $g(\varepsilon_F)$ and q_{TF} increase gradually with increasing n_s instead of the sharp onset expected for an ideal 2DEG.

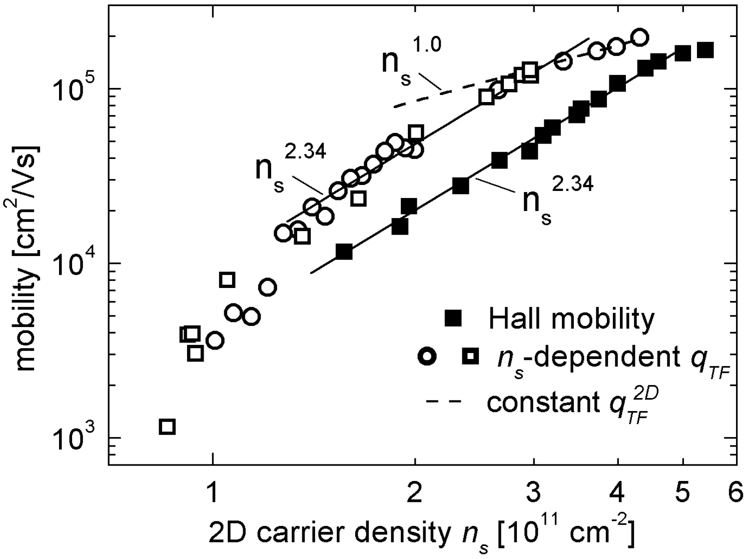

Fig. 2: Hall mobility (solid symbols) and calculated mobility in Thomas Fermi approximation (open symbols) versus n_s. The dashed line represents the ideal 2DCS.

This finding can be explained in terms of potential fluctuations superimposed on the band edge. Such fluctuations may arise from fluctuations of the well width, of the barrier composition, the distribution of ionized donors in the doping layer and residual charged impurities.

In order to test whether these potential fluctuations are the reason for the limited mobility we calculate the mobility within the Thomas-Fermi approach and compare the results to experimental data [5] given in Fig. 2.

As can be seen in Fig. 2, the experimental data differ from the values obtained from q_{TF} by less than a factor of 2 and the exponent is perfectly reproduced.

3. Conclusion

The agreement of the data derived from the ESR susceptibility with the directly measured mobility shows that the mobility is limited by the potential fluctuations that also cause the band tails close to the conduction band edge. The high mobility values seen, at least for high carrier density, show that screening is efficient within the 2DEG. At low carrier density localization occurs and the metal to insulator transition [6], [7] takes place where screening fails and the potential fluctuations tend to diverge [8].

The high mobilities seen indicate rather smooth, long range potential fluctuations. The ESR susceptibility alone does not give direct information on the typical length scale of these fluctuations. There is, however, another quantity which allows to determine a lower limit for the typical extension of the fluctuations in space, namely the ESR line width. The ESR line width is affected by all magnetic moments seen by electrons. This implies a lower limit for the area over which carriers can move freely, because the minimum CESR line width is given by the hyperfine interaction with nuclear spins in the probing area. With the relative abundance of 4.7% of ^{29}Si (the only stable Si isotope with nuclear spin) and the hyperfine constant of P in Si we estimate a minimum extension of the electron wave functions on the order of 1 μm^2. This value is in good agreement with spatially resolved compressibility measurements on GaAs hole channels [9]. Rather large extensions are also consistent with transport experiments on similar samples that revealed in the metallic regime Dingle ratios well in excess of 10. At such high values potential fluctuations are mainly due to the Coulomb potential of the ionized donors in the remote doping layer. These cause inherently smooth fluctuations, and thus large puddles in the insulating regime, since short-range fluctuations decay very fast with increasing spacer thickness.

Acknowledgements

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