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Magnetotransport in GaAs δ-doped by Sn

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Abstract

We have investigated the magnetotransport properties of vicinal (0 0 1) GaAs structures misoriented by 3° towards the (1 1 0) direction. The structures are δ-doped with Sn which predominantly accumulates at the step edges. In this way a dense array of 1D channels ($d = 54$ Å) is formed. Shubnikov–de Haas oscillations show the presence of several subbands. A clear anisotropy in the electronic parameters is observed for a current ∥ and ⊥ to the step edges, notably $R_{\perp}/R_{\parallel} \sim 1.5$ (at $T = 4.2$ K) for a sample with an electron density $n_{\mathrm{Hall}} = 8 \times 10^{12}$ cm^{-2}. We have also found a significant anisotropy in n_{Hall}, μ_{Hall} and n_{SdH}. The difference in n_{Hall} and μ_{Hall} could be explained by preferential scattering in one direction, caused by a preferential attachment of the Sn atoms on the step edges. For the difference in n_{SdH} there is no clear explanation. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: Magnetoresistance; Delta doping; Vicinal substrates

1. Introduction

Advanced epitaxial growth techniques have made it possible to fabricate artificial structures with reduced dimensionality [1]. An appealing method to produce quasi-1D conducting wires is the organised growth on misoriented substrates. For this purpose GaAs substrates misoriented by a small angle from the (0 0 1) plane towards the (1 1 0) basal plane may be used. The vicinal (0 0 1) surface of the GaAs crystal then consists of a system of steps and terraces, with a terrace width of 54–540 Å for a typical misorientation angle in the range 3–0.3°. By decorating the steps with an active donor impurity, e.g. Si or Sn, it should be possible to obtain 1D channels, or at least, a 1D periodic modulation of the 2D electron gas (2DEG). A narrow doping profile may be obtained by δ-doping [2].

In the course of a feasibility study of the fabrication of such structures, we here report on a first characterisation, by means of magnetotransport measurements, of 3° vicinal GaAs structures doped by Sn. Results on 0.3° vicinal GaAs structures doped by Sn were previously reported in Ref. [3]. Sn is an n-type dopant in GaAs and is rarely used for δ-doping because of its high segregation ability [4]. On the other hand, Sn is less amphoteric compared to the usual dopant Si. We have previously reported on the properties of singular GaAs structures δ-doped by Sn [5]. This study served as a basis for the growth of comparable structures on vicinal substrates.

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In the literature some results have been reported on Si δ-doping on vicinal GaAs substrates [6,7]. Although a preferential attachment of the Si atoms to the step edges was observed by RHEED [6], no significant difference between the resistance measured for a current along and perpendicular to the step edges was found. Because of the higher segregation velocity of Sn, we expect that the Sn atoms accumulate more easily at the step edges. Indeed, as will be presented here below, with Sn it is possible to observe anisotropy in the electronic properties.

2. Experimental

The vicinal GaAs samples δ-doped with Sn were grown by MBE on a GaAs(Cr) substrate misoriented by 3° from the (0 0 1) plane towards the (1 1 0) plane. The structure is schematically shown in Fig. 1. The distance between the step edges is 54 Å for a misorientation angle of 3°. On the substrate a buffer layer of 1 μm is grown in the step-flow mode. At a temperature of 450°C a Sn layer was deposit in the presence of an arsenic flux. After the Sn was deposited, a layer of GaAs was grown at a low epitaxy temperature, which ensures formation of a large number of growth islands on the terraces between the step edges. This should maintain a non-uniform distribution of Sn. From the wavers Hall-bars were prepared with the current channel in the (1 1 0) direction, i.e. for a current flowing along the step edges (|| configuration), and with the channel in the perpendicular direction (⊥ configuration). The Hall effect and magnetoresistance were measured at a temperature of 4.2 K in pulsed magnetic fields up to 38 T. The typical pulse duration is 1 s.

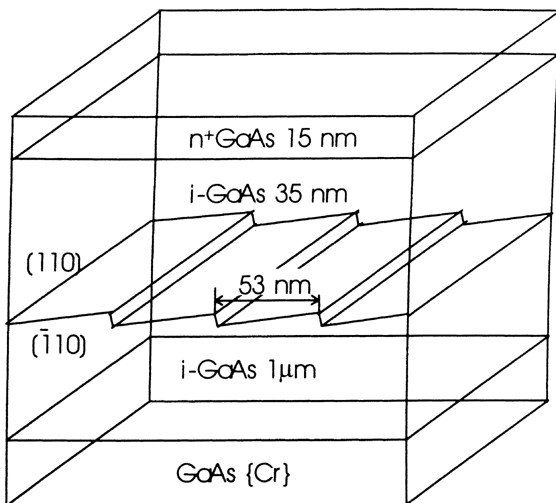

Fig. 1. Schematic drawing of the GaAs (δ-Sn) structure.

3. Results and discussion

We here report on the magnetotransport properties of two 3° vicinal GaAs structures δ-doped with Sn, labelled #1 and #5. The structures were prepared in an identical way, except for the design density of Sn atoms, which was much lower for the latter sample. For both structures we have measured the magnetoresistance and Hall effect in the || and ⊥ configurations. We first concentrate on sample #5. The magnetoresistance (see Fig. 2(a)) shows pronounced Shubnikov–de Haas (SdH) oscillations. The Fourier transform of the data (see Fig. 2(b)) indicates the presence of two subbands. The carrier densities determined from the SdH period (n_{SdH}) and the Hall data (n_{Hall}) are listed in Table 1, together with the quantum mobility (μ_q) [8] and Hall mobility (μ_{Hall}). There is a clear anisotropy in the resistance, $R_{\perp}$ is about 50% larger than $R_{\|}$ at $T=4.2$ K, which provides evidence that we have indeed succeeded in preferentially depositing Sn at the step edges (such an anisotropy was not observed in the singular structures [5]). Furthermore, a significant difference is observed between $n_{Hall,\|}$ and $n_{Hall,\perp}$. Also, $n_{SdH,\|}$ is larger than $n_{SdH,\perp}$ for both subbands. The difference increases for the higher-index subband, which has a lower electron density. We have verified that these differences in resistivity and electron density are not caused by a macroscopic inhomogeneity of the wafer, as different samples taken from distant parts of the same wafer show similar electron densities and a similar current direction dependent behaviour. The derived electron densities and mobilities of different samples of the same wafer #5(#1), show a maximum spreading of 5% (3%),

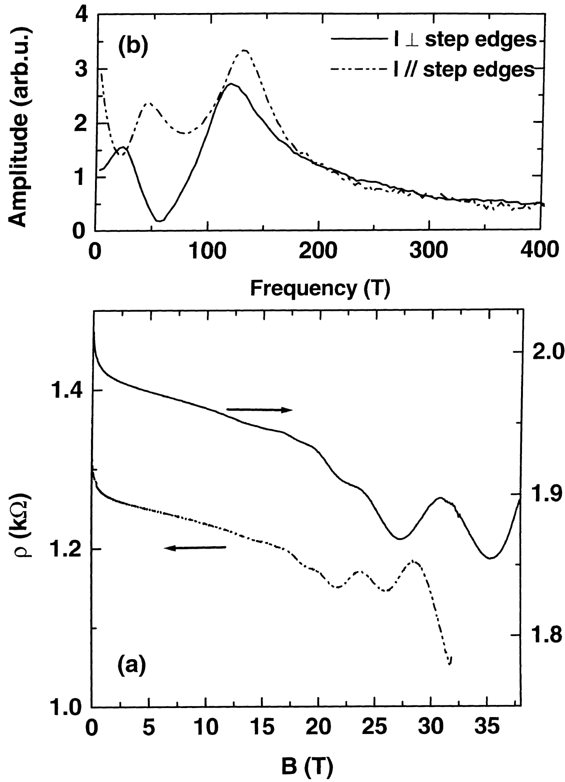

Fig. 2. (a) Magnetoresistance of sample #5 at $T = 4.2$ K for a current along (full line) and perpendicular (dashed–dotted line) to the step edges. (b) Fast Fourier transform of the data in (a).

due to inhomogeneity, which is much smaller than the anisotropy.

The segregation of Sn to the step edges causes a inhomogenous distribution of Sn donor atoms. This anisotropy in the distribution of Sn atoms could lead to a preferential scattering in the direction perpendicular to the step edges. Therefore a higher resistance is observed when the current is perpendicular to the step edges. The anisotropy in n_{Hall} and μ_{Hall} could in principle be explained by the same explanation, but is more difficult to address since several subbands are present. At this stage the anisotropy in n_{SdH} cannot be explained

The magnetoresistance data and the Fourier transform of the data for sample #1 are shown in Fig. 3(a) and (b), respectively. The Fourier transform shows the presence of four subbands. The electron density deduced from the Hall data is about a factor 5 higher than for sample #5 (see Table 1). An anisotropy in the resistance ($R_{\perp}/R_{\parallel} \sim 1.1$ at $T = 4.2$ K) and in the electron density is found, like for sample #5. The results are very similar to the ones for sample #5, but the anisotropy is less pronounced. This smaller anisotropy could be caused by the more homogeneous distribution of Sn donor atoms in sample #1. The effect of repulsion between dopant atoms is bigger in the heavier doped sample #1.

Table 1
Carrier densities determined from the Shubnikov–de Haas period (n_{SdH}) and the Hall data (n_{Hall}), and the quantum (μ_q) and Hall mobility (μ_{Hall}) at $T = 4.2$ K for vicinal (3°) GaAs structures δ-doped with Sn, labelled #1 and #5, for a current along (‖) and perpendicular (⊥) to the step edges

Sample	Subband index	n_{SdH} (10^{12} cm^{-2})	μ_q (cm^2/V s)	n_{Hall} (10^{12} cm^{-2})	μ_{Hall} (cm^2/V s)
#1 ‖	0	8.23	660	38.3	810
	1	4.73	1080		
	2	2.13	1490		
	3	0.92	5400		
#1 ⊥	0	8.45	430	35.5	840
	1	4.62	590		
	2	1.92	645		
	3	0.64	–		
#5 ‖	0	6.26	225	7.97	587
	1	2.19	–		
#5 ⊥	0	5.75	186	5.87	527
	1	1.15	–		

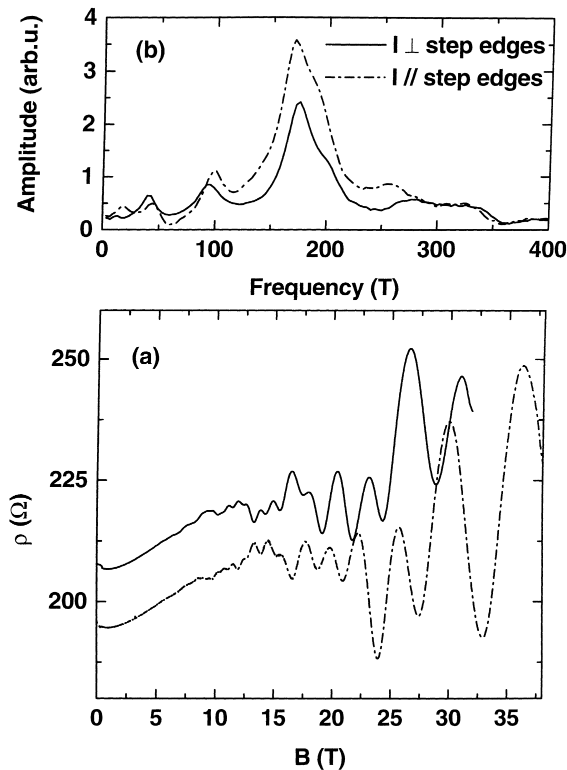

Fig. 3. (a) Magnetoresistance of sample #1 at $T=4.2$ K for a current along (full line) and perpendicular (dashed–dotted line) to the step edges. (b) Fast Fourier transform of the data in (a).

This first characterisation of our 3° vicinal GaAs structures δ-doped with Sn shows that we are able to produce a significant anisotropy in the electronic structure $\parallel$ and $\perp$ to the step edges. This yields support for a 1D modulation of the 2DEG. However, hard proof in the form of e.g. Weiss oscillations, which are found in the case of a weakly modulated 2DEG, [1,9] is lacking. The condition to observe Weiss oscillations in our structures is only met in very high magnetic fields ($B > 50$ T), because of the short modulation period (54 Å). On the other hand, no anisotropy in the resistance was reported for the structures that exhibit Weiss oscillations [9]. From this we expect that our vicinal GaAs samples are beyond the weak modulation regime. In that case one might expect to observe superlattice effects [10], but again the short modulation period makes it difficult to observe such effects.

4. Conclusions

We have investigated the magnetotransport properties of vicinal (3°) GaAs structures δ-doped with Sn for two different Sn doping densities. SdH oscillations show the presence of several subbands. A clear anisotropy in the electronic parameters is observed for a current $\parallel$ and $\perp$ to the step edges, especially $R_{\perp}/R_{\parallel}$ amounts to 1.5 (at 4.2 K) for a sample with an electron density $n_{\mathrm{Hall}} = 8 \times 10^{12}$ cm^{-2}. We have also found a significant anisotropy in n_{Hall}, μ_{Hall} and n_{SdH}. The difference in n_{Hall} and μ_{Hall} could be explained by preferential scattering in one direction, caused by a preferential attachment of the Sn atoms on the step edges. For the present there is no explanation for the difference in n_{SdH}.

Acknowledgements

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References

[1] C. Weisbuch, B. Vinter, Quantum semiconductor structures, Academic Press, San Diego, 1991; C.W.J. Beenakker, H. van Houten, Quantum transport in semiconductor nanostructures, in: H. Ehrenreich, D. Turnbull (Eds.), Solid State Physics, vol. 44, Academic Press, San Diego, 1991, pp. 1–140.

[2] See for a review on delta-doping: E.F. Schubert (Ed.), Delta-doping of semiconductors, Cambridge University Press, 1996.

[3] A. de Visser, V.I. Kadushkin, V.A. Kulbachinskii, V.G. Kytin, A.P. Senichkin, E.L. Shangina, JETP Lett. 59 (1994) 363.

[4] J.J. Harris, D.E. Ashenford, C.T. Foxon, P.J. Dobson, B.A. Joyce, J. Appl. Phys. A33 (1984) 87.

[5] V.A. Kulbachinskii, V.G. Kytin, R.A. Lunin, M.B. Vvedenskiy, V.G. Mokerov, A.S. Bugaev, A.P. Senichkin, R.T.F. van Schaijk, A de Visser, P.M. Koenraad, to be published.

[6] L. Däweritz, K.J. Friedland, J. Behrend, P. Schützendübe, Phys. Stat. Sol. A 146 (1994) 277.

[7] V.A. Kulbachinskii, N.B. Brandt, V.G. Kytin, V.I. Kadushkin, A.P. Senichkin, E.L. Shangina, Phys. Low. Dim. Struct. 12 (1995) 237.
[8] E. Skuras et al., Semicond. Sci. Tech. 6 (1991) 535.
[9] D. Weiss, K. von Klitzing, K. Ploog, G. Weinmann, Europhys. Lett. 8 (1989) 179.
[10] K. Ismail, W. Chu, D.A. Antoniadis, H.I. Smith, Appl. Phys. Lett. 52 (1988) 1071.