Shubnikov-de Haas - Like Oscillations in the Vertical Transport of Semiconductor Superlattices

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Oscillations in the vertical magneto-transport of a *GaInAs-AlInAs* superlattice were observed and explained as being the modulation of miniband properties. We explain that such a modulation is due to the Landau levels of the highly (*Si*) n^+ doped regions. It is shown that phase and amplitude of these oscillations are dependent on the angle between electric and magnetic fields. This phenomenon is thus similar to the Shubnikov - de Haas effect in bulk materials, even though the active region of the superlattice is not intentionally doped. Very highly doped three-dimensional regions were grown on each side of the superlattice to allow for the process of Ohmic contact formation.

The electronic structure of semiconductor superlattices gave rise to the concept of minibands and minigaps of energy [1]. Due to the newly engineered periodicity, electrons can undergo Bloch oscillations via Bragg reflection. Very high-frequency oscillator devices, with superlattices comprising their active regions, have exhibited such behavior. Frequencies as high as 60 GHz with *GaAs-AlAs* superlattices have recently been reported [2]. $GaAs$-$Ga_{1-x}Al_xAs$ superlattices were often studied in the past, but such materials have been replaced in recent years by equivalent $GaIn_{1-x}As_x$-$AlIn_{1-y}As$ structures, which are more attractive for application in telecommunication devices.

Transport properties of superlattices have been extensively studied. There are basically two different configurations available for studying transport in superlattices: *i*) when carriers are moving parallel to the layers; or *ii*) when they are moving perpendicular to the layers. Parallel transport properties of superlattices are more frequently studied because in this case better facilities exist for sample processing.

Furthermore, very important properties like negative differential conductance due to negative effective mass of superlattices occur in the vertical transport regime. Sibille and co-workers observed the negative differential velocity [3] effect in undoped short period *GaAs-AlAs* superlattices. Studying miniband conduction of slightly n^+ doped superlattices, they then directly observed the bulk-like regime of negative differential conductance [4].

Superlattices in presence of a magnetic field applied parallel to the layers have already been studied in detail [5, 6]. Effects such as negative magneto-resistance and in-plane redistribution of electron energy were observed. The influence of interface fluctuations on the vertical miniband transport properties of superlattices has also been observed with the help of a magnetic field applied in the plane of the layers [7]. Effects of miniband conduction are usually well explained by a semi-classical approach, based on the solution of the Boltzmann transport equation.

When the magnetic field is parallel to the current, no classical effect is expected to modify the miniband transport properties. However, oscillations of magneto-resistance corresponding to the magneto-phonon effect have been observed for $GaAs$-$Ga_{1-x}Al_xAs$ superlattices [8, 9]. Such an effect corresponds to resonance of phonon energy with the Landau levels separation induced on the miniband energy. Due to the complete quantization when magnetic energy is superior to the miniband width, leading to a quasi-one-dimensional system [10, 11], magneto-phonon resonance in superlattices is stronger than in bulk materials. The effect of doped regions, growth for contact deposition, on the transport properties of superlattices present still some very important questions to be completely understood [12].

Many recent works studying the effect of tilted magnetic field in semiconductor complex structures have been presented [13, 14]. Henriques et al. investigated the quantum mobility of different minibands on δ-doped superlattices [15]. In this paper we studied a sample in which electrons flowing through the miniband had their properties modulated by the contact regions. The physical effects occurred outside the superlattice active region and modified the current intensity. Our aim was to verify how the miniband magneto-transport properties were modified by external growth parameters.

Highly n^+ (Si) doped regions have been grown on each side of the superlattice to provide ideal conditions for deposition of Ohmic contacts. We measured the conductivity at low temperature of a *GaInAs-AlInAs* superlattice. The electrical field was applied between top and bottom contacts and we observed a modulation of the current intensity J as a function of the magnetic field.

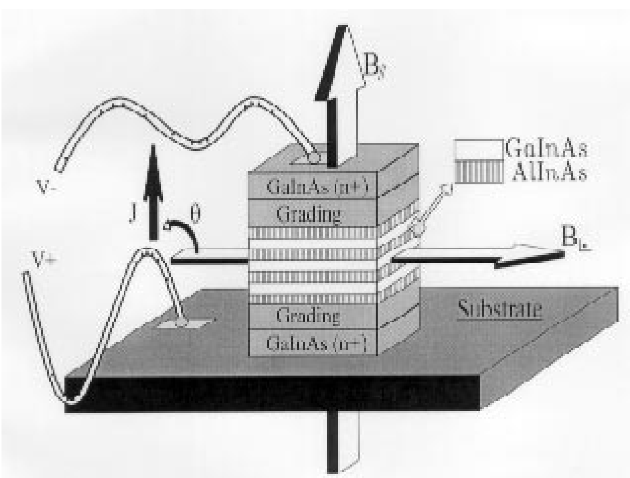

Figure 1. Schematic representation of our magneto-transport experiment. The sample was a *GaInAs-AlInAs* superlattice, matched to bulk *InP*. Magnetic field was initially applied parallel to the layers and then rotated into the plane containing the growth axis. We measured *I(B)* characteristics for different values of the angle θ between the magnetic field and the current density. All measurements were performed at $T = 2\ K$.

To determine the origin of such oscillations we studied their phase and their amplitude as a function of the angle θ defined between the electric and magnetic fields. The sample was fixed to a rotating insert placed in the center of a stationary magnetic field, which was initially applied parallel to the layers ($\theta = 90°$). Different configurations were obtained turning the sample in the plane defined by the growth axis and B. In the final configuration the magnetic field was applied perpendicular to the layers ($\theta = 0°$). The schematic setup of our experiment is represented in Fig. 1.

We explain our observations as a Shubnikov - de Haas - like effect. The Shubnikov - de Haas effect in bulk materials is evidenced by oscillations of the magneto-conductivity. Such oscillations indicate the resonance of Landau levels with the Fermi level energy [16]. Landau levels appear in the three-dimensional electron gas of our sample, i.e., in the very highly n^+ doped regions. We recall that the active region of our superlattice was not intentionally doped. The current through the miniband was, therefore, modulated by the Shubnikov - de Haas effect occurring in the contacts.

The sample was a *GaInAs-AlInAs* structure grown by molecular beam epitaxy on a semi-insulating substrate and was matched to bulk InP material. The superlattice period was equal to 85 Å, of which 45 Å was the well width and 40 Å the barrier width. The first conduction miniband for this structure was 27 meV wide. Highly n^+ doped regions ($2 \times 10^{18} cm^{-3}$) were grown on each side of the periodic structure, in order to allow deposition of Ohmic contacts. A grading average of the composition was carried out between the superlattice active region and n^+ doped layers, in order to avoid abrupt heterojunctions in the passage of the three-dimensional electron gas from contacts to the miniband. Standard lithographic processes with dry etching were performed and "mesas" of area typically in the range of 100 μm have been obtained. *AuGeNi* was deposited and diffused on both top and bottom n^+ doped layers, thus giving perfect Ohmic contacts for our sample. The active region was not intentionally doped, but it had a residual concentration of $n^- \sim 2 \times 10^{16} cm^{-3}$.

F_c is the electrical field for which current intensity is maximum, i.e., F_c is the value indicating the beginning of negative differential conductance. Such a field is closely related to the mean scattering time of electrons in the conduction miniband, as can be seen from a very simple calculation: the Esaki-Tsu model [1], for example. When B is in the plane of the layers the critical electrical field F_c increases as B increases, essentially due to the in-plane movement induced by the crossed field configuration [5, 6]. Conversely, the in-plane energy is separated into Landau levels when B is applied in the growth direction, introducing a new confinement for high enough values of the magnetic field, notably for $\hbar eB > m^*\Delta$ (where Δ is the miniband width and m^* is the in-plane effective mass) [17, 18]. In this case F_c remains almost constant and the current intensity J decreases due to this "quasi-one-dimensional" situation. It is therefore evident that the free electron path (i.e. the mean scattering time) is modified by the magnetic field depending on its orientation with respect to the electric field. We measured the current through the miniband as a function of the magnetic field, while the applied electric field was kept constant. It's well know that Shubnikov - de Haas effect depends directly on the electron temperature [19], but we restrict our study to the low electrical field limit, compared to F_c. Fig. 2 shows the current-magnetic field $I(B)$ characteristic obtained for $\theta = 90°$. Modulation of current intensity is directly detected from the measured curve (straight line). The second derivative (dashed line) of such a curve has been calculated to enhance the oscillatory effect. Oscillations appear much more clearly and are very similar to the Shubnikov - de Haas effect.

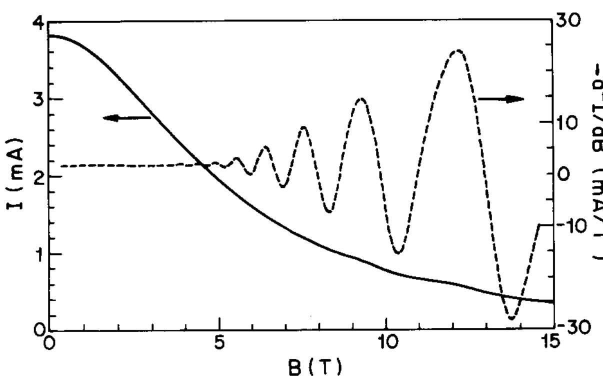

Figure 2. A current-magnetic field intensity $I(B)$ characteristic obtained for $\theta = 90°$. Dashed line represents the second derivative, calculated from experimental results in order to amplify the effect of current modulation. Oscillation is periodic as a function of B^{-1}, which is a characteristic of the Shubnikov - de Haas effect.

Four curves obtained in the same experimental conditions are shown in Fig. 3. The only difference among these curves is the relative position of electric and magnetic fields: $\theta = 90°, 60°, 30°$ and $0°$ for each curve respectively, as defined in the insert. Such oscillations are periodic as a function of B^{-1} and their amplitudes decrease as the temperature increases, typically disappearing for $T \approx 150$ K. We note that: *i*) the phase; and *ii*) the amplitude are dependent on θ. The phase difference appears between the two limit positions of magnetic field. Maxima (minima) observed for $\theta = 90°$ correspond exactly to minima (maxima) observed for $\theta = 0°$. The phase difference is therefore equal to π.

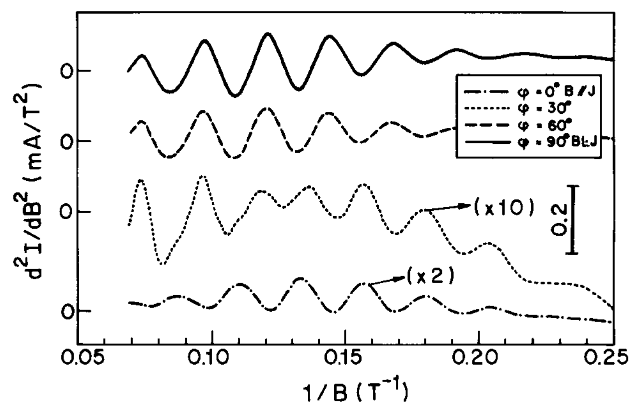

Figure 3. Second derivative of the current-magnetic field intensity characteristics obtained for $\theta = 90°, 60°, 30°$ and $0°$. We remark that results for $\theta = 30°$ and $\theta = 0°$ have been multiplied by factor 10 and 2 respectively, to appear in the same scale. Zero reference has been shifted to facilitate observation. Two main effects are noted: *i*) maxima for $\theta = 90°$ are minima for $\theta = 0°$; and *ii*) amplitude of oscillations is larger for $\theta = 90°$, decreasing as θ decreases and are minimal for $\theta \approx 30°$.

The largest amplitudes of oscillations were obtained when $\theta = 90°$, and the smallest were obtained for $\theta = 30°$. Note that such a curve $\theta = 30°$ has been multiplied by factor 10 and the curve for $\theta = 0°$ has been multiplied by factor 2, in order to plot them on the same scale. Parallel magneto-resistance is small, therefore, when compared to the strong transverse magnetoresistance, which can even be negative in certain conditions [5, 6]. We concluded that such observations stem from two different physical responses of the system, which cancel out for $\theta \approx 30°$, as can be seen if we follow the curves from $\theta = 0°$ up to $\theta = 60°$ in Fig. 3. It seems to be clear that this variation appearing on the amplitude of oscillations describes a competition between two different physical effects, as discussed above.

Such oscillations are in essence identical to the Shubnikov - de Haas effect observed in bulk materials. However, the active region of the superlattice was not intentionally doped, indicating that this effect was not originated into the miniband. We used a well known relationship to calculate three-dimensional electronic density from the frequency of such oscillations:

$$N_{3D} = \frac{1}{3\pi^2}\sqrt{\left(\frac{2e}{\hbar}B_f\right)^3} \tag{1}$$

where $B_f = 42\ T$ is the "fundamental magnetic field", taken from Fig. 4.

We obtain:

$$N_{3D} = 1.5 \times 10^{18} cm^{-3}$$

which is approximately the nominal value for the doping concentration of n^+ doped regions. We therefore concluded that the current flowing through the miniband was modulated by the Landau level separation occurring in n^+ doped regions. Even if the active region of the superlattice was not doped, we observed a Shubnikov - de Haas - like effect due to modulation of miniband transport properties. Similar results were obtained in the past with a single barrier in the place of our periodic superlattice [20].

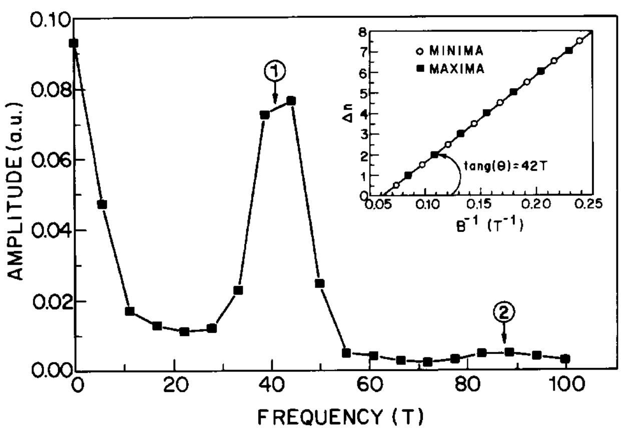

Figure 4. Fourier Transform and peak analysis (in the insert) for oscillations of $I(B)$ characteristics. We obtained the fundamental magnetic field $B_f = 42\ T$ corresponding to $N_{3D} = 1.5 \times 10^{18} cm^{-3}$, which is very close to the nominal concentration of the n^+-doped regions $N_{nom} = 2 \times 10^{18} cm^{-3}$, growth to allow Ohmic contact formation.

In order to explain the exact difference of phase observed in our experiment, we used a semi-classical description of electrons in presence of a strong magnetic field. We started from the point of view that almost all free electrons are near the Fermi level (ε_F) at $T = 2\ K$ and, consequently, the number of electrons passing in the miniband increases when a Landau level coincides with (ε_F).

When the magnetic field is applied perpendicular to the current, electrons are deviated from their initial straight line trajectory along the growth direction and a portion of their total energy is redirected to the plane of the layers. It is therefore evident that, in this case, the presence of scattering processes will assist electronic transport along the electric field direction, breaking the magnetic confinement. Maximum current modulation therefore occurs when scattering process is at a maximum.

Conversely, electronic movement is more restrained to growth direction when the magnetic field is applied parallel to the current intensity, due to the Landau levels in the plane of the layers. Consequently the electronic scattering will obstruct current flow in this configuration. A minimum of the current oscillation in this configuration corresponds then to a situation where the scattering process is maximized. In spite of the qualitative explanation presented until now, this experiment showed an effective way to study quantitatively the scattering process on such a superlattice.

Some authors discussed the conductivity in similar system and equivalent configurations. Neudert *et al.*[21] presented the analytical expression below for the diagonal magneto-conductivity, in which they introduced the "scattering conductivity" into the quantum Kubo formula:

$$\sigma_{\mu\mu} = \frac{2\pi}{n_\phi}(\hbar\omega)^2 \int dE \left(-\frac{df}{dE}\right)\sigma_{\mu\mu}(E) \tag{2}$$

where $f(E)$ is the distribution function. The nondiagonal components of such a tensor are:

$$\sigma_{\mu\nu} = \frac{4}{n_\phi}(\hbar\omega)^2 \int dE f(E)\sigma_{\mu\nu}(E) \tag{3}$$

Dependence on the rotation angle θ due to the "scattering conductivity" is included in $\sigma_{\mu\mu}(E)$ and $\sigma_{\mu\nu}(E)$. A more similar work compared to our study was very recently presented by Mal'shukov, Chao and Willander [22], in which they verified the anisotropy of the quantum Hall effect with respect to the direction of magnetic field in the plane parallel to interfaces. In their model they found the following relation:

$$\frac{\sigma_{yx}}{\sigma_{Hall}} = A\frac{\tau_{so}\tan\theta}{\tau\sin\phi} \tag{4}$$

where $\cos\theta \propto (\tau_{so}\tau)^{1/2}$, ϕ is the angle between the magnetic field and the interface, τ_{so} is the scattering time due to spin-orbit interaction, τ is the total scattering time and A is a structural parameter (see ref. [22]). Such recent works indicate a very attractive and actual study of magnetotransport properties of semiconductor heterostructures. It is also evident that a more detailed quantitative analysis remains to be done to explain our results, even though a good qualitative explanation was obtained.

In conclusion, oscillations of vertical magnetotransport of semiconductor superlattice were observed and explained as being a "Shubnikov - de Haas - like effect". Modulation of miniband conduction was due to quantum effects occurring in highly doped regions and was dependent on the electric and magnetic fields configuration. We qualitatively explained such effects using a semi-classical description and taking into account the role of electronic scattering processes to the miniband transport.

Acknowledgments

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References

[1] L. Esaki and R. Tsu, IBM Journal of Research and Development **14**, 61 (1970).

[2] A. Sibille, J. F. Palmier, H. Wang, J. C. Esnault and F. Mollot, Solid-State Electronics **32**, 1461 (1989).

[3] A. Sibille, J. F. Palmier, H. Wang and F. Mollot, Phys. Rev. Lett. **64**, 52 (1990).

[4] A. Sibille, J. F. Palmier, F. Mollot, H. Wang and J. C. Esnault, Phys. Rev. B **39**, 6272 (1989).

[5] F. Aristone, A. Sibille, J. F. Palmier, D. K. Maude, J. C. Portal and F. Mollot, Physica B **184**, 246 (1993).

[6] F. Aristone, J. F. Palmier, A. Sibille, D. K. Maude, J. C. portal and F. Mollot, Solid State Electronics **37**, 1015 (1994).

[7] F. Aristone, J. F. Palmier, P. Gassot, J. C. Portal and F. Mollot, App. Phys. Lett. **67**, 2916 (1995).

[8] H. Noguchi, H. Sakaki, T. Takamasu and N. Miura, Phys. Rev. B **45**, 12148 (1992).

[9] P. Gassot, J. Genoe, D. K. Maude, J. C. Portal, K. S. H. Dalton, D. Symons, R. J. Nicholas, F. Aristone, J. F. Palmier and F. Laruelle, Phys. Rev. B**54**, 14540 (1996).

[10] V. M. PolyanovskII, **14**, 828 (1980).

[11] V. M. PolyanovskII and Nguyen Hong Shon, Sovietic Physics Semiconductor **24**, 1857 (1983).

[12] L. A. Cury, D. K. Maude, F. Aristone, J. C. Portal, D. L. Sivco, A. Y. Cho and G. Hill, Surface Science **267**, 383 (1992).

[13] Mayumi Kato, Akira Endo, Shingo Katsumoto and Yasuhiro Iye, Phys. Rev. B **58**, 4876 (1998).

[14] G. R. Facer, B. E. Kane, R. G. Clark, L. N. Pfeiffer and K. W. West, Phys. Rev. B **56**, R10036 (1997).

[15] A. B. Henriques,L. C. D. Gonçalvez and N. F. Oliveira Jr, Phys. Rev. B **55**, 13072 (1997).

[16] Yu. A. Firsov, V. L. Gurevich and R. V. Parfeniev. Landau levels spectroscopy. 1992, *Semiconductor and Semimetals*, Elsevier Science B. V., P. O. Box 211, 1000 AE Amsterdam, The Netherlands, **27.2**

[17] V. M. PolyanovskII and Nguen Hong Shon, Sovietic Physics Semiconductors, **17**, 208 (1983).

[18] V. M. PolyanovskII, Sovietic Physics Semiconductors **23**, 1037 (1989).

[19] Nicholas, R. J. and J. C. Portal. *Transport in Semiconductors*, Plenum Press, New York, 1980, p. 255

[20] T. W. Hickmott. Phys. Rev. B **32**, 6531 (1985).

[21] R. Neudert, P. Rotter, U. Rössler and M. Suhrke, Phys. Rev. B **55**, 2242 (1997).

[22] A. G. Mal'shukov, K. A. Chao and M. Willander, Phys. Rev. B **57**, R2069 (1998).