Photoexcited carriers in single-asymmetric-quantum-well structures

I.F.L.Dias
D.F. - CCE - Universidade Estadual de Londrina
Caixa Postal 6001- Cep 86055-900, Londrina, PR, Brazil

J. C. Bezerra, R. C. Miranda and A. G. de Oliveira
D.F.- Inst. de Ciências Exatas - UFMG
Caixa Postal 702 - Cep 30161, Belo Horizonte, MG, Brazil

Recebido em 18 de maio, 1995

Isothermal (77 K) photoexcited Hall concentration n_H and mobility μ_H measurements, using an infrared LED, were investigated for three single asymmetric quantum well (SAWS) samples grown by MBE on the AlGaAs system using silicon as doping element. The influence as a function of the accumulated light dose, on both n_H and μ_H were mainly analysed changing the quantum well and alloy doped layer widths. We observed that n_H increases with the light dosing and decreases when the light is turnned off. The change of μ_H is however more complex since it shows local or absolut maximum for increasing n_H but μ_H presents a monotonic increase when the light is turnned off. This behaviour was explained assuming the presence of two alternative channels for the electron transport and intersubband scattering on the quantum well.

1. Introduction

$Al_xGa_{1-x}As$, with $0 < x < 1$, has attracted much attention due to properties which make it useful for many types of heterojunction device structures such as laser and FET[1]. One important heterojunction in this context is the so called Single Modulated Doped Heterojunction (SMDH), which is the spatial justaposition of two alloys with different compositions, with the higher bandgap material selectively doped with donors, which in turns produce a discontinuity in the potential energy at the interface. A two dimensional electron gas (2DEG) with mobility of 10^6 cm^2/(Vs) are currently obtained at the interface[2]. The main characteristic that propitiates this high mobility is the spatial separation of charge carriers from the charged scattering centers. In spite of this high mobility other relevant properties for devices are not achieved by using this structure. For exemple even weakly electrical fields reduce strongly the mobility[3,4], with direct reflexes in the drain saturation current of FET devices. A way to overcome some of the disavantages are by defining, through the growth procedure, a spacealy narrow quantum well. It consists of an undoped GaAs well sandwiched by silicon doped layers. This symmetrically modulated doped quantum well (SMDQW) shows low mobilities, whichwere associated to the presence of the inverted interface (GaAs grown upon AlGaAs)[5,6] and to the surface segregation of silicon ocurring at high growth temperatures[7,8]. A single asymmetrically quantum well (SAQW) selectively doped was introduced to avoid the negative effects of the inverted interface. Structure properties can be optimized by changing the quantum well width, therefore increasing the distance between the 2DEG and the inverted interface. This way, higher 2DEG concentration as well as higher saturation currents in FET devices can be obtained if compared to SMDH[4,9,10].

All these heterojunctions show high dependence on illumination after they are cooled in the dark to low temperatures (< 100 K) if the AlGaAs layer has a composition higher than 20% aluminum[9−11]. The isothermal measured Hall electron concentration nH increases strongly even at low level of illumination and it persists for long periods of time after the light is turnned off[11]. This persistent photoconductivity (PPC) is commonly attributed to an unusual deep level in n-type AlGaAs, denoted DX center[12] and it coexists with the expected hidrogen-like shallow (d) donor centers[13,14]. It seems now well established that the DX center is an intrinsic feature of the n-type dopant[15]. We have shown before[16] a strong evidence that the negatively charged centers are the only or at the least the dominant deep centers related to silicon impurities in AlGaAs, supporting the so called U-negative model[17,18]. The isothermal increase of n_H as a function of the accumulated time of illumination follows basically an exponential function, stablishing a saturation value at the condition of maximum ionization of the DX centers. The results reported in the literature however, show a more complicated behaviour for the mobility μ_H. First, it shows an increase as a function of increasing n_H and then it decreases and sometimes it starts to increase again, showing a maximum. Sometimes it looks like a small shoulder. The decreasing occurs at different values of n_H and is basically dependent on sample parameters. Two different phenomena have been usually independently used to explain this behaviour: whether the parallel conduction with electrons at the conduction band in the doped supply AlGaAs layer or the intersubband scattering when others then the fundamental quantum level for the 2DEG are populated[19−24]. Both phenomena can be produced by optical excitation temperatures[9,10,24−27]. In the present work we describe the isothermal variation of n_H and μ_H with the acummulated time of illumination for SAWQ structures. We prepare three SAQW structures, with different quantum well widths L_z, which is the critical parameter to define the number of occupied subbands. To analyse the parallel conduction we used two different values for the doped AlGaAs layer lenght L_D. Observation on the variation of n_H and μ_H were also carried out when the light was turned off after the saturation condition for n_H has been attained.

2. Experimental Details

The SAQW structures were grown by MBE on (001) oriented, undopel semi-insulating GaAs substrates. A non-intentionally doped GaAs buffer layer, 0.2 μm thick, was grown for all samples. Following the buffer layer a non-intentionally doped alloy with x=0.34 and thickness L_B, was grown. The GaAs quantum well, with thickness L_z, was then grown. A 100 Å non-intentionally alloy spacer was grown and it was followed by a uniformly doped alloy layer with thickness L_D. The structure was finished with a 150 Å thick film of n^+ uniformely doped GaAs to prevent the surface depletion layer from affecting the region of the quantum well. The doped alloy layer has a nominally silicon concentration of $N_{\mathrm{Si}} = 5 \times 10^{17}$ cm^{-3}. The L_B, L_Z and L_D values as well as the growth temperature are shown in Table I. To improve the inverted interface quality we interrupted the growth during 30 s before we startet to growth the GaAs quantum well. The alloy composition of 0.34 was confirmed by photoluminescence measurements. The silicon doping level was assessed by CV measurements. the samples are 5 × 5 mm^2 with contacts made on the top surface by alloying 10 min at 400°C in a N_2 atmosphere an indium ball at each corner. The samples, cooled in darkness to 77 K, were uniformly illuminated using an infrared LED ($h\nu = 1.32$ eV) mounted in the cryostat. Hall measurements were then carried out in the dark and also under illumination using the van der Paw geometry. All samples were cooled in darkness by immersing them in liquid nitrogen and therefore an abrupt cooling was used. Electrical measurements were undertaken as a function of accumulated ligth dose by illuminating the sample repetitively for time intervals of 30 s, keeping the LED current at 1 mA. Hall electron concentration n_H and mobility μ_H were then recorded 2 min after the LED was turnned off. This 2 min delay was demanded for to give the charge carrier distribution time to reach his quasi-steady state[25] and the measurements could be taken in a PPC regime. The relatively low mobilities found for our samples are indeed expected due to small the L_z for two samples[28,29] and due to the low V/III flux ratio for the third one.

3. Results

Table I shows the electrical results for n_H and μ_H obtained at room temperature under ambient light and at 77 K in darkness. The n_H values at room temperature give information about the available electrons in alloy doped layer. The values at 77 K in darkness give information about the cooling efficiency for the DX center formation. In Fig. 1 we plot the observed Hall electron mobility against the Hall electron concentration measuring with increasing ligth dose at 77 K. The first point in each curve, represents the values shown in Table I. Under our experimental conditions, the n_H values increase monotonously following a tipical exponential function until its saturation which are indicated in Fig. 1 by the three arrows. The saturation conditions were in fact confirmed by strongly increasing the illumination intensity and any change in n_H were not of the observed. The singular aspects ofthe curves in Fig. 1 should be associated to the complex behaviour of the mobility as we mention before. A common characteristic of the three μ_H versus n_H curves are the initial increases until they reach a maximum, which in sample #86 is a local one but not for the other two. The n_H values at this maximum are in the range of (6.8-7.6)$\times 10^{11}$ cm^{-2}. The mobility values at the saturation condition for n_H are also indicated by the three arrows. It is smaller than the initial value in darkness for sample #108; it is higher for sample #107 and it is the maximum value for sample #86. After the saturation condition for n_H, the LED was turnned off and n_H and μ_H values are recorded during 40 min. During this time n_H decreases and n_H increases for the three samples. We noted two peculiarities in the curve for the sample #107. μ_H tends to recover its maximum value following parallel the track measured under illumination. The observed step for the mobility at the saturation condition for n_H was associated to the amount of final illumination before the LED was turnned off.

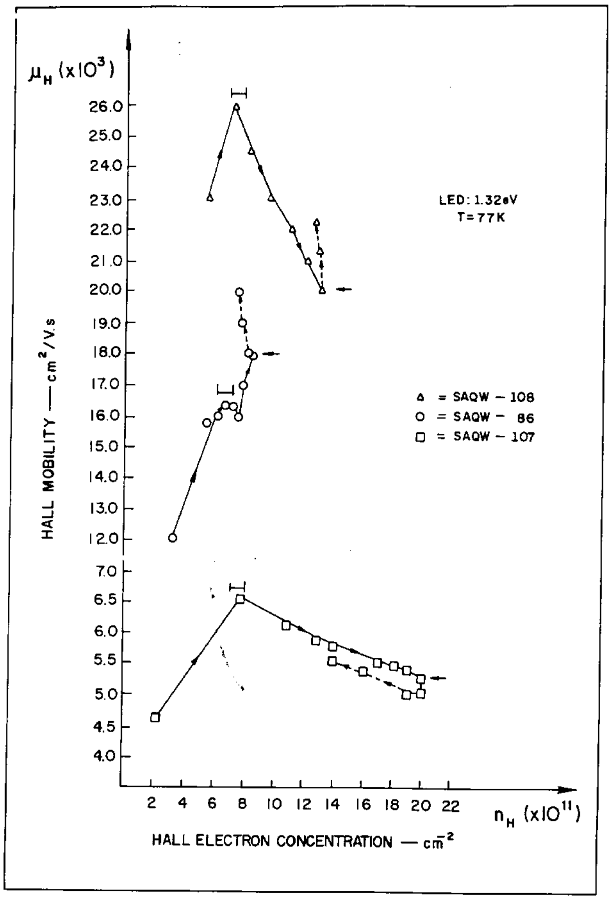

Figure 1. Hall mobility as a function of the Hall electron concentration for the three samples at 77 K. The n_H saturation values are indicated by arrows.

4. Discussion

We observed that the n_H values at 77 K recorded in darkness increase with a respective increasing in the quantum well width. This observation agrees with theoretical previtions[28,29]. In the same way μ_H recorded in darkness increases with the quantum well width, what

Sample#	T_S (K)	R (V/III)	L_z (Å)	L_D (Å)	300 K		77 K	
					n_H	μ_H	n_H	μ_H
SAQW-107	873	0.6	80	1000	7.7	1.6	2.3	4.7
SAQW-86	900	1.7	120	600	4.2	3.5	3.1	12.0
SAQW-108	873	0.6	190	1000	9.2	2.4	5.5	23.0

TABLE 1. Parameters for the SAQW structures: T_S is the substrate temperature, R is the V/III flux ratio for the AlGaAs layers, L_z is the quantum well width, L_D is the AlGaAs doped layer lenght. The spacer L_S is 100 Å. n_H is given in units of 10^{11} cm^{-2} and μ_H in units of 10^3 cm^2/(Vs).

indeed is expected, because the effective distance between the 2DEG and the usually bad quality inverted interface[28,29] increasing. Furthermore, under illumination DX centers are destroyed by the optical excitation contributing to increase the free electron concentration. The behaviour at the first stage, that at which μ_H is increasing, can be explained by using the 2DEG behaviour at its fundamental energy level. Indeed the μ_H increasing is expected, due to a more effective coulombian screening from the anysotropic morphological roughness at the inverted interface and its usually excessive impurities[6,28,29]. It is also expected to increase due to the coulombian screening from the scattering charged center in the alloy doped layer, which is the dominant factor if $T < 77$ K and only the fundamental energy level is occupied[30]. The steady state decays after the maximum value in the samples #107 and #108 are associated with the presence of parallel transport[27] or inter-subband scattering in the quantum well[25].

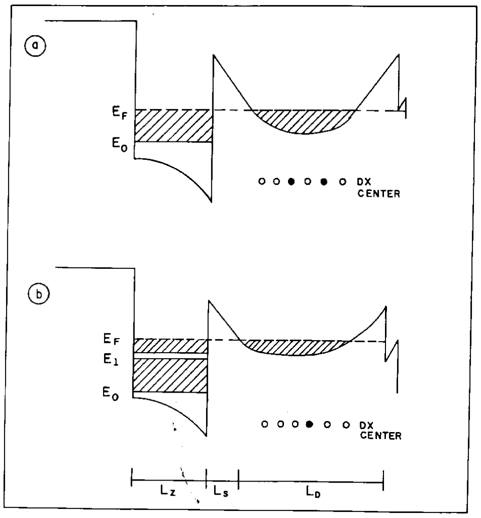

Figure 2. Schematic views of the conduction band for the SAQW structures. The DX center level is shown as well as the band connected with the AlGaAs doped layer in a) a unique subband system and in b) a double subband system.

Parallel transport of selectively doped structures can start when the Fermi energy level reaches the conduction band bottom of the alloy doped layer. From this point two channels for charge transport are present. One at the quantum well having high mobility values (1) and other at the doped AlGaAs layer having low mobility (2). This two channels transport model is illustrate in Fig. 2. The weight of the second channel increases with n_H and therefore the effective measured mobility reduces continously[27]. Indeed, what is ploted in Fig. 1 is the effective mobility which yields information about all possible transport mechanism. The occurrence of parallel conductance in SMDH and others heterostructures depends on a number of sample parameters like: the thickness of AlGaAs layer L_D, the doping concentration N_{Si}, the thickness of undoped AlGaAs spacer layer, the aluminium mol fraction x, the thickness of GaAs cladding layer[9,10]. The important parameter to define whether parallel transport will take place is the total silicon atoms available to produce free charge carriers which is determinated by the product $L_D \times N_{\mathrm{Si}}$. This product is therefore the quantitative parameter to determine or not the presence of parallel conduction. Using available L_D and N_{Si} values from the literature [19-24] we found that the critical value for parallel transport is about $L_D \times N_{\mathrm{Si}} = 3 \times 10^{12}$ cm^{-2}. The samples, with higher alloy doped concentration, #107 and #108 have $L_D \times N_{Si} = 5 \times 10^{12}$ cm^{-2} which therefore satisfy conditions for parallel transport. The sample #86 which seems to be at the critical limit has a value of $L_D \times N_{\mathrm{Si}} = 3 \times 10^{12}$ cm$^-2$. Its μ_H versus n_H curve show however a local maximum which can be associated to the presence of parallel transport. Similar results of #107 and #86 curves are found in the literature for SMDH samples[25] and the behaviour were associated to the intersubband scattering. This is however not allowed for our samples since the first excited level is not occupied. In conclusion we believe that all our samples present parallel transport, which is indicated by the maximum in the μ_H versus n_H curves for n_H in the range of 6.8-7.6 $\times 10^{11}$ cm^{-2}.

The effect of intersuband scattering was already theoretically analised for SMDH and SMDQW structures[19]. They show that the first excited subband starts to be occupied for $n_{2\mathrm{DEG}} = 1 \times 10^{12}$ cm^{-2} for SMDH and 7×10^{11} cm^{-2} for SMDQW. Values for $n_{2\mathrm{DEG}}$ as low as 5×10^{11} cm^{-2} for SMDH were already reported in the literature[25]. The energy for the first excited subband was calculated and compared to the fundamental subband[31]. For sample #108 the energy difference between the two subbands was 33 meV. Therefore, the probability of intersubband scattering is not negligible mainly if we take into account that n_H as high as 10^{12} cm^{-2} was achieved at the saturation condition. The presence of intersubband scattering besides the parallel conduction can be explained if the more fast decay of mobility in sample #108 is comparable to sample #107. This could also explain the smaller value for the mobility at the saturation condition when compared to the value in darkness. Photoluminescence measurements show indeed the first excited subband occupation[32]. Theoretical calculations show that due to the small L_z values the first excited subband does not take part in the transport process for samples #86 and #107 [33]. Photoluminescence measurements also show no occupation of the first excited subband[32]. After the last dose of light, when the optical excitation procedure is finished, it is expected that the free electron concentration starts to reduce tending to recover the initial concentration. The period of time necessary to show significant recovering can however be very large due to PPC effects[11]. We recorded the recovering during 40 minutes for the three samples. An increase in the mobility and, as expected, a reduction in the free electron concentration were observed for the three samples. The mobility behaviour indicates that the free electron concentration reduces with priority for low mobility channels. The recovery for sample #107 follows aligned with the excitation curve, what suggest the presence of only parallel transport. Otherwise, the recovery for sample #108 is very abrupt what suggest the presence of the first excited subband depopulation in agreement to other articles[19,34,35]. This agrees also with the early mentioned photoluminescence results and theoretical calculations concerning to the presence of the first excited subband occupation. In this case therefore the mobility is defined by charge transport in different channels, namely the fundamental subband, the alloy doped layer and the first excited subband. For sample #86 the occupation of first excited subband is not expected, because the energy separation between the two first subbands is too high. Indeed, photoluminescence and theoretical calculation corroborate to this evidence. Thus parallel conduction is present in this sample because a clear local maximum exists for n_H at 6.8×10^{12} cm^{-2}. The product $L_D \times N_{\mathrm{Si}} = 3.0 \times 10^{12}$ cm^{-2} is close to the limit that parallel conduction is supposed to start which accounts then for the increase after the local maximum. It is exactly this critical situation that accounts for the mobility increasing after the optical excitation. The depopulation will occur predominantly from the low mobility channel and the abruptness suggest that the 2DEG concentration is only lightly disturbed.

5. Conclusion

The isothermal dependence of n_H and μ_H as a function of the accumulated time of illumination using a infrared LED was used to study parallel conduction and intersubband scattering in single asymmetric quantum wells (SAQW). The two possible channels for the charge carriers transport are the GaAs quantum well and the AlGaAs doped layer. The intersubband scattering takes place when the first excited subband on the GaAs quantum well starts to be occupied. Parallel conduction were indeed observed on the three prepared samples since local maximum were present on the μ_H versus n_H curves in the range $(6.8 - 7.6) \times 10^{11}$ cm^{-2}. In the present work the parameter used whether to define or not the presence of the parallel conduction was the product $L_D \times N_{\mathrm{Si}}$, i.e., the product of the AIGaAs doped layer lenght by the silicon concentration. Using the available gathered data from the literature we calculated the critical figure as 3×10^{12} cm^{-2} which agrees with our results.

We acknowled financial support by Brazilian agencies FINEP, CNPq and FBB.

References

1. R. Dingle, in *Semiconductors and Semimetals*, edited by R. K. Williardson and A. C. Beer, volume 24, Academic Press, New York, 1988.
2. G. Weimann, in *Festkorperprobleme (Advances in Physics)*, edited by P. Grosse, volume 26, page 231, Vieweg, Braunscheweig, 1986.
3. K. Inoue and H. Sakaki, Jpn. J. Appl. Phys. **23**, 61 (1984).
4. C. Guillemot, M. Baudet, M. Gauneau, A. Regreny, and J. C. Portal, Phys. Rev. B **35**, 2799 (1987).
5. H. Burkhard, W. Schlapp, and G. Weimann, Surf. Sci. **174**, 382 (1976).
6. C. Delalande, Phys. Script. **T19**, 129 (1987).
7. H. Markoç, T. J. Drummond, R. E. Thorne, and W. Kopp, Jpn. J. Appl. Phys. **20**, L913 (1981).
8. T. J. Drummond, et al., Appl. Phys. Lett. **42**, 615 (1983).
9. E. F. Schubert, K. Ploog, H. Dambkes, and K. Herme, Appl. Phys. A **33**, 63 (1984).
10. E F. Schubert, K. Ploog, H. Dambkes, and K. Herme, Appl. Phys. **A 33**, 183 (1984).
11. E. F. Schubert, A. Fischer, and K. Ploog, Phys. Rev. **B 31**, 7937 (1985).
12. D. V. Lang, R. A. Logan, and M. Jaros, Phys. Rev. **B 19**, 1015 (1979).
13. M. F. Li, Y. B. Jia, P. Y. Yu, J. Zhou, and J. L. Gao, Phys. Rev. **B 40**, 1430 (1989).
14. Y. B. Jia, et al., J. Appl. Phys. **66**, 5632 (1989).
15. P. M. Mooney, J. Appl. Phys. **67**, R1 (1990).
16. I. F. L. Dias et al., Solid State Comm. **77**, 327 (1991).
17. D. J. Chadi and K. J. Chang, Phys. Rev. Lett.**61**, 873 (1988).
18. D. J. Chadi and K. J. Chang, Phys. Rev. **B 39**, 10063 (1989).
19. S. Mori and T. Ando, J. Phys. Soc. Japan **48**, 865 (1980).
20. S. Hiyamizu, T. Mimura, T. Fujii, and K. Nanbu, Appl. Phys. Lett. **37**, 805 (1980).
21. S. Hiyamizu, K. Nanbu, T. Mimura, T. Fujii, and H. Hashinito, Jpn. J. Appl. Phys. **20**, L378 (lY81).
22. S. Hiyamizu and T. Mimura, J. Crystal Growth **56**, 455 (1982).
23. S. Hiyarnizu, J. Saito, K. Nanbu, and T. Ishikawa, Jpn. J. Appl. Phys. **22**, L609 (1983).
24. H. L. Storrner, A. C. Gossard, W. Wiegmann, and K. Baldwin, Appl. Phys. Lett. **39**, 912 (1981).
25. A. Kastalsky and J. C. M. Hwang, Solid State Commun. **51**, 317 (1984).
26. D. J. Newson te al., J. Phys. C**19**, L403 (1986).
27. C. E. Falt et al., Semicond. Sci. Technol. **2**, 513 (1987).
28. D. C. Radulsecu, G. W. Wicks, W. J. Schaf, A. R. Calawa, and L. F. Eastman, J. Appl. Phys. **61**, 2301 (1987).
29. D. C. Radulsecu, G. W. Wicks, W. J. Schaf, A. R. Calawa, and L. F. Eastman, J. Crystal Growth **81**, 106 (1987).
30. C. M. Hurd, S. P. McAlister, D. J. Day, and J. Stich, J. Appl. Phys. **64**, 5225 (1988).
31. V. M. S. Gomes, A. S. Chaves, J. R. Leite, and J. M. Worlock, Phys. Rev. **B 35**, 3984 (1987).
32. W. M. Mendes, Ms. Thesis, PUC, Rio de Janeiro, 1990.
33. L. Scolfaro, private communication.
34. T. Englert, J. C. Maan, D. C. Tsui, and A. C. Gossard, Solid State Commun. **45**, 989 (1983).
35. J. J. Harris et al., J. Appl. Phys. **61**, 2250 (1987).