Photoconductivity in AlSb/InAs quantum wells

Ch Gauer†, J Scriba†, A Wixforth†, J P Kotthaus†, C Nguyen‡, G Tuttle‡, J H English‡ and H Kroemer‡

† Sektion Physik, Universität München, D-8000 München 22, Federal Republic of Germany
‡ QUEST Center, UC Santa Barbara, CA 93106, USA

Abstract. Measuring photoconductivity at low temperatures, we investigate the recently observed bipolar behaviour of the persistent photoeffect in InAs/AlSb quantum wells. Depending upon the incident wavelength we observe either a persistent increase or a persistent decrease of the carrier density in the well. We discuss our experimental findings in terms of a simple model based on the band structure as known to date and the growth parameters of the heterostructure.

1. Introduction

Recent advances in molecular beam epitaxy have made it possible to grow even complex, lattice-mismatched heterojunctions. One such system is the material combination consisting of GaSb, AlSb and InAs which offers a wide variety of applications as tunnel diodes [1], mid-infrared detectors [2] or hot-electron transistors [3].

Due to their relative novelty, many basic properties of such complicated systems are not well documented to date. One question that is still not fully resolved is the origin of mobile carriers in nominally undoped InAs quantum wells between AlSb barriers [4]. The search for the responsible donor is quite advanced [5], but further studies are highly desirable.

Here, we would like to report on photoconductivity (PC) measurements of the AlSb/InAs/AlSb system. This material combination yields quantum wells with unusually high conduction band offsets and confinement energies. A sketch of the expected band diagram of the investigated samples is depicted in Figure 1. The relatively complicated sequence of buffer layers between the active region and the GaAs substrate has been omitted for clarity. Such buffer layers relieve the strain between the substrate and the active layers and have been described elsewhere [4]. A GaSb cap layer on top of the surface prevents the AlSb from reacting with water moisture if exposed to air. AlSb is an indirect-gap ($\Delta E_X = 1.61$ eV) semiconductor with a direct gap at the centre of the Brillouin zone of $\Delta E_\Gamma = 2.3$ eV. The band structure related to the direct gap is indicated by the broken lines. The InAs bandgap is about $\Delta E_\Gamma = 360$ meV and the valence band offset to the AlSb barrier is $\Delta E_V \approx 100$ meV. The resulting quantum well depth is thus $V_0 \approx 1.35$ eV. The low effective mass in InAs ($m_\Gamma^* = 0.023 m_0$) results in large confining energies of approximately 60 meV for the lowest electrical subband in a well 12 nm wide.

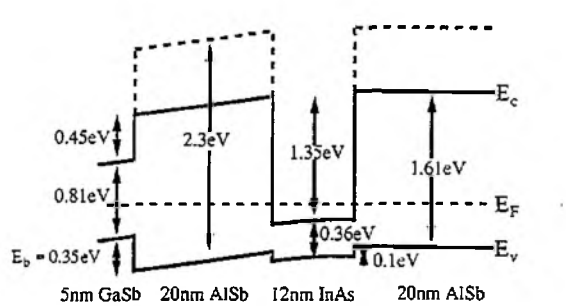

Figure 1. Band structure of the investigated samples. Eighty per cent of the carriers in the well are assumed to originate from the GaSb cap layer [5] which gives rise to the built-in electric field in the top AlSb barrier.

The optical properties of this material combination are also very remarkable. It is well known that in some semiconductor heterojunctions the carrier density can be tuned by bandgap radiation due to persistent photoconductivity. The most prominent example is the AlGaAs/GaAs system, where an increase of the carrier density in the quantum wells is attributed to electron photoexcitation from DX centres [6] in the AlGaAs layer. Recently, there has also been a report on a reduction of the carrier density in AlGaAs/GaAs quantum wells [7] if they are continuously illuminated by AlGaAs bandgap radiation. A persistent reduction of the carrier density in InAs/AlSb quantum wells has already been observed for very early samples [4]. Later, we discovered a persistent increase of the carrier concentration if the energy of the illuminating light is smaller than the AlSb bandgap. Here, photoconductivity is measured to reveal the spectral dependence of the persistent photoeffects with this unusual bipolar behaviour. Such experiments have proved to be a powerful tool for characterizing the response of semiconductors to illumination [8].

2. Experiment

A sketch of our experimental set-up is given as an inset of figure 2. The sample is illuminated with monochromatic light ranging in energy from $h\nu = 1.0$ eV to $h\nu = 3.0$ eV. A 1000 W xenon lamp and a grating monochromator serve as the light source. Using a 600 μm multimode optical fibre the light is coupled into the sample which is mounted within an He cryostat. The sample is mesa etched into a Hall bar geometry and has alloyed indium contacts. We determine the sample resistance at 4.2 K using four-terminal measurements and low-frequency standard lock-in techniques at alternating current.

A typical result of such a PC measurement is shown in figure 2 for sample A. Here, we plot the measured voltage at the potential probes under continuous illumination as a function of the incident light energy. This voltage is found not to depend strongly on the light intensity and is proportional to the sample resistance, namely

$$U_{xx} \propto j/eN_s\mu$$

where j denotes the current through the structure, e the elementary charge and N_s and μ the carrier density and the electron mobility, respectively. The horizontal line in the graph denotes the initial resistance value in the dark that was measured after cooling the sample to 4.2 K.

Upon illumination the sample resistance is lowered for photon energies smaller than about $E_{ph} \approx 1.55$ eV and increases for photon energies above this value. The light energy at which the cross-over from the negative to positive photoeffect occurs depends on the sample composition. For different samples the energies varied from $E_{ph} = 1.25$ eV to $E_{ph} = 1.55$ eV. The resistance under continuous illumination remains nearly constant below $E_{ph} \approx 1.3$ eV and then rises as the incident light energy increases. This photoconductive effect is persistent, i.e. after switching off the light the resistance is still far off its initial dark value even after one hour. The time constants involved are still under investigation

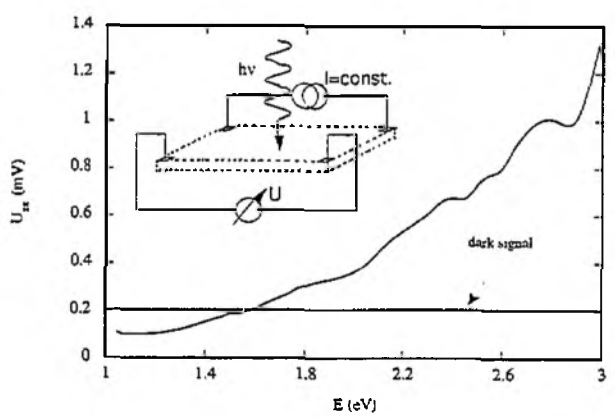

Figure 2. Photovoltage U_{xx} of sample A as a function of the incident light energy. The dark signal corresponds to a photon energy of $E_{ph} \approx 1.55$ eV. A sketch of the experimental set-up is depicted in the inset.

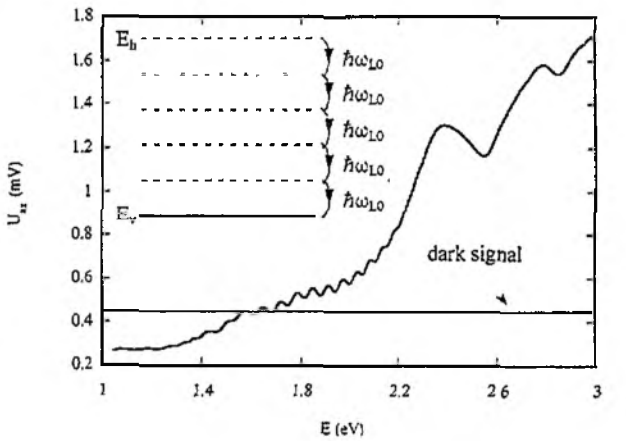

Figure 3. Photovoltage U_{xx} of sample B as a function of the incident light energy. The dark signal corresponds to a photon energy of $E_{ph} \approx 1.55$ eV. A phonon cascade, which is believed to cause the oscillations of the photovoltage, is shown in the inset.

and will be discussed elsewhere. Cyclotron resonance measurements in the far infrared [9] reveal how the mobility and carrier density change for different light energies. In sample A, for example, the electron density varies from 0.5×10^{12} cm^{-2} at $E_{ph} = 2.25$ eV to 2.1×10^{12} cm^{-2} at $E_{ph} = 1.30$ eV while the mobility rises from 28 000 cm^2 V^{-1} s^{-1} to 40 000 cm^2 V^{-1} s^{-1}. The change in mobility is traced back to the more effective screening of Coulomb scatterers for high carrier concentrations. At specific photon energies the photoconductive signal shows some features which are related to the band structure of the heterojunction. Before we discuss these features in detail, we would like to show for comparison the spectrum of the similarly grown sample B. In figure 3 we plot again the resistance as a function of the incident light energy under continuous illumination. The most prominent feature is a very pronounced oscillatory structure in U_{xx} between $E_{ph} \approx 1.35$ eV and $E_{ph} \approx 2.3$ eV. When we illuminate the sample with light whose energy corresponds to the resistance extrema and then measure the carrier density in the dark we find that N_s also oscillates. Such oscillations are not observed on any other sample but they are reproducible for sample B. The overall signature of the PC spectra shown in figure 1 and figure 2 is very similar and reveals the same trend as all other samples we investigated.

3. Interpretation

We attribute the decrease in the sample resistance (compared with the dark value) for light energies smaller than about 1.55 eV to the photoionization of deep donors. The nature and the ionization energies of those donors have yet to be determined. The interpretation of the PC spectra taken under continuous illumination, to which the rest of this paper is devoted, will explain why the resistance rises for photon energies above this threshold, i.e. the negative PC.

We believe that the sample resistance increases around $E_{ph} \approx 1.3$ eV, since for this value the kinetic energy of the photogenerated holes in the GaSb cap layer is such that they may overcome the potential barrier of the GaSb/AlSb interface. Then they can diffuse towards the quantum well along the potential gradient of the built-in electric field. This potential gradient is specifically strong in these samples since 80% of the free carriers originate from surface donors in the cap layer [5]. The holes recombine with the electrons in the quantum well, thus reducing their net concentration. The photogenerated electrons, on the other hand, will neutralize the surface donor [10] and thereby not contribute to the PC. According to this model the photon energy $h\nu_{on}$ at which the resistance begins to rise is determined by the height of the potential barrier E_b given by the valence band offset between the GaSb and the AlSb layer

$$h\nu_{on} = E_g + E_b\left(1 + \frac{m_h^*}{m_e^*}\right).$$

Here, E_g is the GaSb bandgap and m_h^* and m_e^* denote the light hole and the electron mass in GaSb. Accounting for the non-parabolicity of the electron mass in GaSb with a two-band Kane model [11] the valence band offset is calculated to be $E_b \approx 0.32$ eV in agreement with the value determined by Cebulla *et al* [12]. The reduction of the carrier density for light energies greater than 1.3 eV cannot be explained by the photoexcitation of electrons from the well. In this case the resistance should begin to increase at $E_{ph} \approx 1.2$ eV, which is the energetic difference between the Fermi level and the top of the AlSb barrier. PC measurements of other samples in which the threshold at $E_{ph} \approx 1.3$ eV is even more pronounced support this point. Secondly, this model cannot account for the oscillations of the resistance in sample B.

The change in the slope of the signal at $E_{ph} \approx 2.3$ eV is related to the direct gap in the AlSb layers. For greater light energies electron–hole pairs can be generated in the barriers and the electrons diffuse into the well while the holes contribute to the recombination. The ratio of the efficiency of the two processes determines how much the slope changes for this energy range. The described structure shifts to lower energies in the spectra taken at 4 K compared with those taken at 77 K. This temperature dependence also indicates that the effect is related to the band structure. At present, we cannot definitely interpret the additional structures at higher photon energies.

We now turn to the description of the oscillations between $E_{ph} \approx 1.35$ eV and $E_{ph} \approx 2.3$ eV in the spectrum of sample B. The period of the oscillations and the wide energy range over which they are observed are indications of intrinsic oscillatory PC as found in many polar bulk semiconductors [13]. Shaw attributes this phenomenon to the relaxation of photoexcited electrons via the emission of LO phonons, which leads to a period of the oscillations equal to $\hbar\omega_{LO}[1 + (m_e^*/m_h^*)]$, where ω_{LO} denotes the phonon frequency and m_e^* and m_h^* are the effective electron and hole masses of the semiconductor in which the carriers are generated. Since in our samples the oscillations start approximately at the same energetic threshold as the increase in resistance discussed above, we believe that the responsible carriers are again the photogenerated holes in the GaSb cap layer, a fraction of which will be injected into the AlSb barrier. In both layers the most effective relaxation mechanism is the emission of LO phonons. The photoexcited holes which relax in the GaSb layer will not contribute to the PC in contrast to those reaching the barrier. If the kinetic energy of the latter with respect to the AlSb valence band is a multiple of $\hbar\omega_{LO}$(AlSb) they thermalize very rapidly and will be collected by the quantum well. If the kinetic energy, however, does not match a multiple of $\hbar\omega_{LO}$(AlSb) the hole has a greater probability of being transferred back to the cap layer. Thus the number of holes in the barrier, and consequently the resistance of the two-dimensional electron system, reaches a local minimum. Analysing the periodicity of the oscillations we find that the period decreases almost linearly from 80 meV at $E_{ph} \approx 1.35$ eV to 50 meV at $E_{ph} \approx 2.3$ eV. Since the period should be equal to

$$\hbar\omega_{LO}(\text{AlSb})[1 + (m_h(\text{GaSb})/m_e(\text{GaSb}))]$$

the deviation from exact periodicity might be caused by non-parabolicity effects in the GaSb layer. Assuming a constant hole mass and comparing the electron mass extracted from the above formula with the mass obtained in a simple two-band Kane model [11] the agreement is satisfactory, i.e. deviations are less than 5% for low electron energies. A more sophisticated model including strain and band bending effects is under development. The oscillations end at $E_{ph} \approx 2.3$ eV because for greater light energies holes are also generated in the AlSb barrier for which the above matching condition does not hold.

4. Conclusion

In summary, we have measured photoconductivity spectra of AlSb/InAs quantum wells for light energies ranging from 1.0 to 3.0 eV. These spectra indicate that the holes photogenerated in the GaSb cap layer, rather than deep levels in the AlSb barriers [4], determine the negative persistent photoeffect found in those structures, while the positive photoconductivity is explained by the ionization of deep donors. The period of the oscillatory PC observed in one sample should make it possible to calculate the non-parabolicity effects on the electron and hole masses in the GaSb.

Acknowledgments

We gratefully acknowledge very useful discussions with Klaus Ensslin and John M Worlock. This work has been sponsored by the ONR and the Volkswagen-Stiftung.

References

[1] Chen J F, Wu M C, Yang L and Cho A Y 1990 *J. Appl. Phys.* **68** 3040

[2] Parihar S R, Lyon S A, Santos M and Shayegan M 1989 *Appl. Phys. Lett.* **55** 2417

[3] Levi A F and Chiu T H 1987 *Appl. Phys. Lett.* **51** 984

[4] Tuttle G, Kroemer H and English J H 1989 *J. Appl. Phys.* **65** 5239

[5] Nguyen C, Brar B, Kroemer H and English J H 1992 *Appl. Phys. Lett.* **60** 1854

[6] Mooney P M 1990 *J. Appl. Phys.* **67** R1

[7] Kukushkin I V, von Klitzing K, Ploog K, Kirpichev V E and Shepel B N 1989 *Phys. Rev.* B **40** 4179

[8] Moss T S 1980 *Handbook on Semiconductors, 2. Optical Properties of Solids* (Amsterdam: North-Holland)

[9] Scriba J, Seitz S, Wixforth A, Kotthaus J P, Tuttle G, English J H and Kroemer H 1992 *Surf. Sci.* **267** 483

[10] Nguyen C, Brar B and Kroemer H 1992 *J. Vac. Sci. Technol.* B **10** 898

[11] Kane E O 1957 *J. Phys. Chem. Solids* **1** 249

[12] Cebulla U, Tränkle G, Ziem U, Forchel A, Griffiths G, Kroemer H and Subbana S 1988 *Phys. Rev.* B **37** 6278

[13] Shaw R W 1971 *Phys. Rev.* B **3** 3283