AlP/GaP quantum wells for implementing intersubband devices in the 30-60 μm wavelength region

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***Abstract*—A detailed study of inter-subband energy transitions in AlP quantum wells (QWs) based on valley-symmetry and effective-mass measurements using THz cyclotron resonance and quantum transport in AlP/GaP QWs is presented. We show that AlP/GaP QWs can serve as the basis for THz devices emitting in the 30-60 μm wavelength range that is inaccessible by other systems because of phonon band absorption.**

I. INTRODUCTION

In the so-called terahertz gap ranging from 30 to 60 μm, most intersubband optical devices such as quantum cascade lasers or quantum well intersubband detectors cannot operate. because their constituent semiconductor materials (GaAs, InAs and GaInAs) are opaque due to their LO-TO phonon band lying in this wavelength range. Consequently, materials with higher energy phonon bands like GaN, GaAlN or GaP, AlP are needed for covering the THz gap.

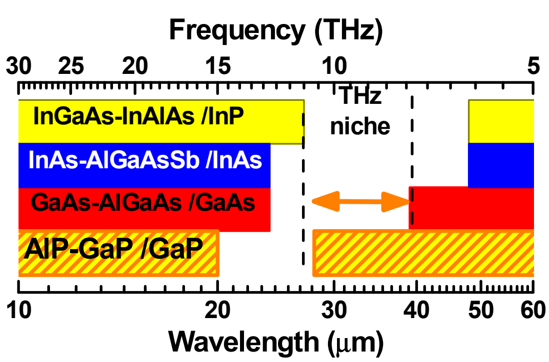

Figure 1 Resthralen absorption bands for heterostructures based on GaAs, InAs and GaP substrate and used as emitters or detectors. AlP/GaP is the most transparent below 10 THz (above 30μm).

This presentation represents a detailed study of intersubband electronic structure of GaP-AlP-GaP quantum wells (QWs) that are grown along the <100> direction on GaP substrates. In this system, as in silicon, electrons occupy X-conduction subbands and are distributed in valleys either parallel or perpendicular to the growth direction. Confinement in the z direction due to GaP barriers results in two ladders of subbands, one is the X_x and X_y valleys where the transverse effective mass m_t determines the subband structure and the other ladder is the X_z-valley where the longitudinal effective mass m_l determines the subband energies. Until recently, the intersubband electronic structure remained unknown in spite of extensive studies of AlP/GaP heterostructures for optoeletronic emitters of green light. This is because electrons effective masses have not been measured in bulk AlP. Evidently, for designing QWs structures having intersubband energies in the THz gap, knowledge of X-subbands valley-symmetry, valley-ordering and valley-degeneracy, as well as longitudinal and transverse electron effective masses is a basic requirement. AlP/GaP heterostructures, in addition of being widely transparent in the THz spectrum, offer unique properties of X-Valley quantum well electron structure, actually not provided by silicon based X-valley systems. This includes tunable valley crossover which takes place because of strain effect due to the small lattice mismatch between AlP layer and GaP substrate.

The presentation below reports THz cyclotron resonance (CR) measurements, Quantum Hall Effect, Shubnikov de Haas (SdH) oscillations measurements in a wide range of temperatures down to 2K and at magnetic fields up 60T.

The results are then used to establish intersubband energy transitions and evidence effect of valley-symmetry crossover.

II RESULTS

Samples are silicon-doped in GaP barriers to obtain 2-dimensional electron gas in AlP QWs having thickness ranging from 3 to 10 nm [1], electron concentrations per well falls near $5.10^{11} cm^{-2}$ and mobility in the range of 4.000 cm^2/Vs.

The first result concerns the degeneracy of X-valley subbands and their symmetry. In bulk AlP the X_x, X_y and X_z valleys might be either twofold or non degenerate, depending on whether the X-conduction band minimum lies respectively inside the Brillouin zone or at the X point. This open question was answered by Quantum Hall Effect measurements of the 2-Dimensional electron gas set in AlP/GaP HEMT-type structure. Valley degeneracy g_v was obtained by measuring Landau level filling factors given by the Quantum Hall resistance value at the plateau divided by the Klitzing resistance. At low magnetic fields, Landau levels appear to be both valley- and spin-degenerate therefore the filling factor changes by $2\ g_v$. At high magnetic fields, filling factor changes by one, therefore a straightforward determination of g_v is obtained. We found that AlP QWs narrower than 4 nm have a non-degenerate single valley ground state subband, consequently an X_z-valley symmetry because of uniaxial symmetry. On the other hand, QWs larger than 4nm have twofold degenerate, X_x, X_y valleys as ground state subbands.

The second result summarizes cyclotron resonance effective mass for AlP/GaP multi-quantum wells (MQWs), respectively narrower and wider than 4 nm. Because narrow QWs ground state subbands have X_z-valley-symmetry, their 2D electrons

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Fermi orbit is circular in the xy plane, and characterized by an isotropic transverse effective mass m_t .On the other hand, large QWs have degenerate X_x and X_y ground state subbands with elliptical Fermi orbits characterized by a cyclotron effective mass $(m_t\ m_l)^{1/2}$. Measurements of both cyclotron effective masses, as reported in figure 2, give transverse $m_t = 0.3 \pm 0.02 m_0$ and longitudinal mass $m_l = 0.9 \pm 0.02\ m_0$. Magnetic fields much higher than 5 Tesla were applied to fulfil the condition for Landau quantization $\mu.B>1$. Also, THz excitation signal was required to match the CR condition $2\pi\nu=eB/m^*$, given the high effective mass value expected in this wide gap material.

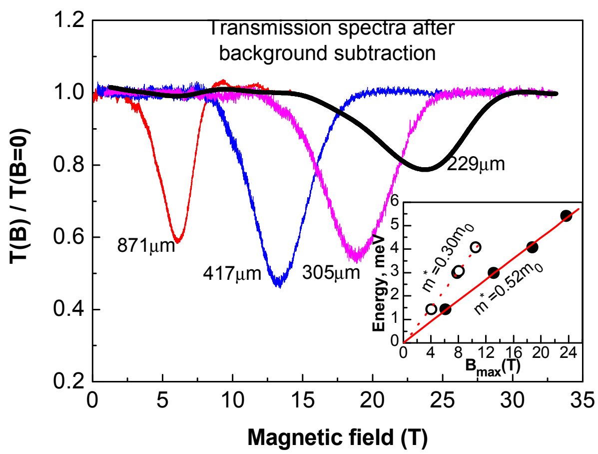

Figure 2 Cyclotron resonance lines for X_x, X_y valleys of a wide multi-QW including 50 wells 10nm, measured in transmission under THz excitation at wavelength 229, 305, 417 and 871 µm, and at temperature T=5K. The insert gives the cyclotron effective mass 0.52 m_0 from the slope of the linear plot photon of energy versus magnetic field. The points on doted line are data for a narrow QW nm with X_z valley. The slope gives $m_t = 0.3 \pm 0.02 m_0$

We also measured the above cyclotron masses using magneto-transport data displaying Shubnikov de Haas oscillations (SdH) on the resistivity, respectively for narrow and wide QWs. Effective masses obtained from analysing the damping of SdH oscillations amplitude with temperature fall in good agreement with CR values.

Let us emphasize that the crossover is caused by a biaxial compression of the AlP layer by the GaP substrate. This compression lifts up X_z valley with respect to X_x, X_y valleys. For narrower quantum wells, confinement prevails and the X_z –valley with heavy-mass-valley along the growth direction is the ground state. As a consequence of crossover, intersubband energy displays a steep increase with thickness since level spacing changes as the reciprocal of the effective mass along the growth direction.

Intersubband absorption in AlP/GaP QWs have been experimentally demonstrated [3] in the spectral range 3-10 µm by measuring FTS spectra using an MCT detector. Samples used were polished into 45° multiple-reflection prism. In the present study we attempted to extend measurements at longer wavelength using a sensitive bolometer. Although we observed a transmission window for single path across the sample face , no signal could be measured across the multiple-reflection prism sample. We then focus on the interpretation of existing data and calculated the intersubband structure on both side of crossover system. Figure 3 summarizes the results, the plain line indicates the fundamental transition (1e-2e) decreasing in energy with well thickness but showing a steep increase at crossover thickness. The dotted line accounts for an excited intersubband transition (1e-4e) that matches the observed peaks represented by circles [3].

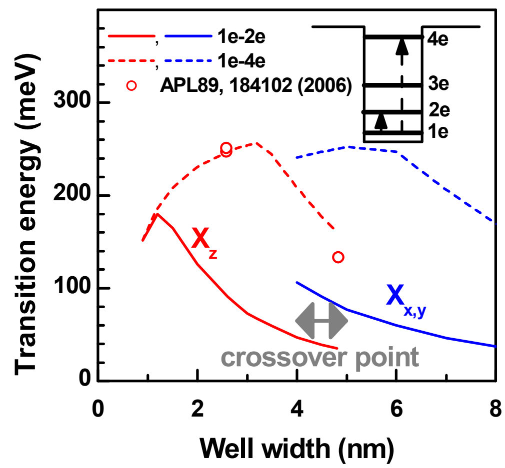

Figure 3 Fundamental inter-subband transitions and valley cross-over in AlP Qws as a function of well thickness.

. In conclusion, the design of THz devices based on AlP/GaP heterostructures is now feasible, based of the X-valley conduction band parameters obtained by THz spectroscopy in high magnetic fields. We believe that QWs based intersuband THz detectors should not suffer from GaP substrate absorption since their active layer is near the surface and thus may reach high quantum efficiency.

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REFERENCES

1- M. P. SEMTSIV, S. DRESSLER, W. T. MASSELINK, V. RYLKOV, J. GALIBERT, M. GOIRAN, AND J. LÉOTIN
Symmetry of the conduction-band minimum in AlP-GaP quantum wells
Phys. Rev. B 74, 041303 (R) 2006
2- M. P. SEMTSIV, O. BIERWAGEN, W. T. MASSELINK, , M. GOIRAN J. GALIBERT, AND J. LÉOTIN
X_t-X_l valleys crossover in AlP-GaP quantum wells
Phys. Rev. B 77, 165327 (2008)
3- M.P. SEMTSIV, U. MULLLER, W.T. MASSELINK, N. GEORGIEV, T. DEKORSKY AND M. HELM *Intersubband transitions in GaP/AlP heterostructures ;* APL 89, 184102 (2006)