M. Montes Bajo, J. Tamayo-Arriola, N. Le Biavan, J. M. Ulloa, P. Vennéguès, D. Lefebvre, M. Hugues, J.-M. Chauveau, A. Hierro, "Intersubband absorption at normal incidence by m-plane ZnO/MgZnO quantum wells," Proc. SPIE 10919, Oxide-based Materials and Devices X, 109192C (1 March 2019); doi: 10.1117/12.2509524

http://dx.doi.org/10.1117/12.2509524

Intersubband absorption at normal incidence by m-plane ZnO/MgZnO quantum wells

M. Montes Bajo, J. Tamayo-Arriola, N. Le Biavan, J. M. Ulloa, P. Vennéguès, et al.

M. Montes Bajo, J. Tamayo-Arriola, N. Le Biavan, J. M. Ulloa, P. Vennéguès, D. Lefebvre, M. Hugues, J.-M. Chauveau, A. Hierro, "Intersubband absorption at normal incidence by m-plane ZnO/MgZnO quantum wells," Proc. SPIE 10919, Oxide-based Materials and Devices X, 109192C (1 March 2019); doi: 10.1117/12.2509524

SPIE.

Event: SPIE OPTO, 2019, San Francisco, California, United States

Intersubband absorption at normal incidence by m-plane ZnO/MgZnO Quantum Wells

M. Montes Bajo[1], J. Tamayo-Arriola[1], N. Le Biavan[2], J. M. Ulloa[1], P. Vennégùes[2], D. Lefebvre[2], M. Hugues[2], J.-M. Chauveau[2], and A. Hierro[1]

[1]ISOM, Universidad Politécnica de Madrid, 28040 Madrid, Spain
[2]Université Côte d'Azur, CNRS, CRHEA, 06560 Valbonne, France

ABSTRACT

Intersubband absorption at normal incidence is forbidden by the selection rules and requires oblique incidence operation or texturing of the surface of intersubband-based devices such as focal plane arrays, adding additional processing steps to their fabrication and therefore increasing complexity and costs. Here we demonstrate normal-incidence, polarization sensitive intersubband absorption by wurtzite ZnO/MgZnO quantum wells grown on an m-plane orientation. When grown in this non-polar plane, the ZnO/MgZnO quantum wells spontaneously assemble forming a V-groove profile in the direction perpendicular to the c-axis, i.e. along the a-direction. A stack of quantum wells featuring this morphology acts as a metamaterial that allows for intersubband absorption at normal incidence whenever the electric field of the light is polarized in the direction perpendicular to the c axis. This phenomenon occurs because when the electric field is perpendicular to the c-axis it is no longer contained in the plane of the quantum wells therefore allowing for a small intersubband absorption. On the contrary, if the electric field is parallel to the c-axis, the usual normal-incidence conditions are recovered and no absorption is observed.

Keywords: ZnO, intersubband, quantum well, absorption, infrared

1. INTRODUCTION

Intersubband (ISB) transitions are the backbone of many infrared optoelectronic devices, in part due to the lack of semiconductors with such a narrow band gap. Most of the existing ISB-based devices are based on the GaAs family of semiconductors. However, wide band gap materials have been receiving increasing interest from the research community. Also, ZnO has recently gained attention for its use in ISB devices. Indeed, ISB absorption [1, 2, 3], quantum well infrared photodetectors [1], and more recently, quantum cascade detectors [4] have been demonstrated.

In terms of ISB-based optotelectronic devices for IR detection applications, one has to consider the selection rule for polarization that applies to ISB transitions. This selection rule stems from the calculation of the oscillator strength of the transitions and states that in order to produce electronic transitions between confined levels of a quantum well, the oscillating electric field of the incoming light wave has to be perpendicular to the plane of the quantum wells. In other words, if we name z the direction perpendicular to the quantum wells and xy the plane containing the quantum wells, only the z component of oscillating electric field of an oblique incidence, transverse wave can produce ISB absorption [5].

1.1 Overcoming the polarization selection rule in focal plane arrays of detectors

This selection rule has the implication that a transverse wave that reaches the quantum wells at normal incidence produces no absorption since its electric field lies in the same plane as the quantum wells. This poses a challenge for the fabrication of IR detecting devices because these quantum well structures are usually prepared by layer-by-layer growth techniques and therefore, the most immediate way of fabricating the devices would be to dice the as-grown wafer and glue it onto a

Oxide-based Materials and Devices X, edited by David J. Rogers, David C. Look,
Ferechteh H. Teherani, Proc. of SPIE Vol. 10919, 109192C · © 2019 SPIE
CCC code: 0277-786X/19/$18 · doi: 10.1117/12.2509524

package. In this configuration, the light would impinge normally on the quantum wells and no absorption could be detected. This issue is even more challenging when fabricating focal plane arrays of detectors for IR imaging, since in this case it is virtually impossible to tilt every pixel individually so the light reaches each of them at an oblique incidence angle (say Brewster angle). Therefore, additional processing steps are required for the fabrication of these devices.

A common strategy to circumvent this challenge is to fabricate diffraction gratings on the device, so the propagation direction of the light is changed forcing it to travel through the quantum wells in an oblique manner. Typically, the light reaches the active area of these sort of devices form the substrate. Texturing of the top surface of the structure (i.e. the last layers to be reached by the light) to form a diffraction grating results in the diffraction of the light back into the quantum well structure, this time at an oblique angle of incidence. Thus, the ISB absorption is permitted and the devices are capable of IR light detection and imaging [5].

There are two main ways of implementing these diffraction gratings on the surface of the quantum wells wafers. One is to deposit metallic patterns of some kind [6], the other is to etch away selected areas of the semiconductor surface in order to generate the diffraction grating [7] [8]. These etched patterns can be deep enough to reach and etch the quantum wells themselves, in an approach sometimes termed corrugated quantum wells [9].

If a diffraction grating pattern is etched on every pixel of a focal plane array of detectors, forming a set of parallel grooves, every pixel has a sensitivity not only to light intensity at normal incidence but also to light polarization, since only light polarized perpendicular to the etched stripes would be detected. If the grooves are oriented in different directions, so the nearest neighbors of any pixel have their grooves rotated 45º with respect to the central pixel, this adds polarization sensitivity to the intensity sensitivity of the whole focal plane array, allowing for the use of these devices in polarimetry applications [8].

1.2 V-groove quantum wells made of ZnO

The examples given above unfortunately add complexity and extra steps in the fabrication of the devices. It would be very convenient to have some sort of metamaterial which features a built-in geometry that allows for ISB absorption at normal incidence in a similar way as the examples above. Here we introduce m-plane ZnO/MgZnO quantum wells that feature an as-grown corrugation of the quantum wells that allows ISB absorption at normal incidence with polarization sensitivity just as in the example described above.

M-plane ZnO/MgZnO quantum wells have been reported to feature a V-groove shape along the a-axis [10, 11], i.e. perpendicularly to the c-axis. Please note that in m-plane material both the a- and c-axis lie in the growth plane. The morphology of the QWs allows having a component of the electric field perpendicular to the QWs even at normal incidence as long as the polarization of the incident light is perpendicular to the c-axis, i.e. along the direction of the V-groove shape (see Figure 1, right panel). Under these conditions, some ISB absorption is expected at normal incidence, its strength dependent on the angle of the V-groove shape, i.e. the angle between the electric field and the QWs or, in other words, the size of the component of the electric field that is perpendicular to the QWs.

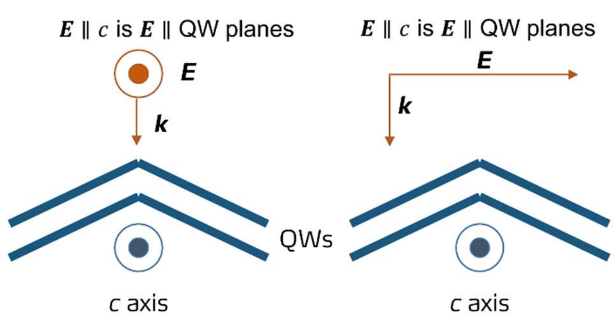


Figure 1. Schematic describing the rationale that explains why there is polarization sensitive ISB absorption at normal incidence in m-plane ZnO/MgZnO QWs.

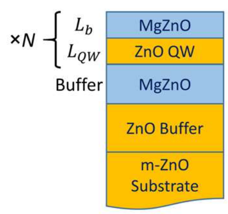
However, if the polarization of the incident light is parallel to the c-axis, the electric field is fully contained in the QW planes and no ISB absorption is permitted. This is in essence the same situation one finds at normal incidence in regular, flat QWs (Figure 1, left panel).

Therefore, as will be demonstrated in the following paragraphs, m-plane ZnO/MgZnO QWs are structures where ISB absorption at normal incidence with sensitivity to the polarization of the incident light is possible.

2. EXPERIMENTAL DETAILS

2.1 Samples in this study

We show two samples in this study, grown by molecular bam epitaxy on m-plane ZnO substrates. Both samples consist of a stack of m-plane ZnO/MgZnO QWs grown atop a MgZnO buffer layer. The QWs are n-type doped with Ga to populate the lowest lying levels of the QWs and allow for light absorption. Sample 1 features 15 periods of 3.6 nm-thick znO QWs with 10 nm-thick MgZnO barriers with 26% Mg content. The MgZnO buffer layer is 50 nm thick and the electron concentration in the QWs is 6.5×10^{19} cm^{-3}. Sample 2 consists of 10 periods of 3.9 nm-thick QWs with 10 nm-thick MgZnO barrier layers with 32% Mg. Its buffer layer is 100 nm thick and the electron density in the QWs is 8.5×10^{19} cm^{-3}. The carrier density in the QW is obtained from fits to reflectance experiments as described in [2].



	Sample 1	Sample 2
N	15	10
L_{QW} (nm)	3.6	3.9
L_b (nm)	10	10
Buffer (nm)	50	100
n (10^{19} cm^{-3})	6.5	8.5

Figure 2. Schematic describing the samples presented in this work.

2.2 Transmission experiment

The transmittance of the samples was measured in a Fourier transform infrared spectrometer (FTIR) that allows measurements in the range 400 to 7000 cm^{-1}. The samples are mounted on a goniometer that permits to select the angle of incidence of the light. A holographic wire grid polarizer on a KRS-5 substrate is used to set the polarization of the incident light either contained in or perpendicular to the plane of incidence.

3. RESULTS AND DISCUSSION

3.1 Intersubband transition at 50º and at normal incidence

The first step in this study is to verify the presence of ISB transitions. The transmittance of the samples is measured under both s and p polarization of the incident light at 50º of incidence of the incoming light. The s to p transmittance ratio is plotted in Figure 3. Clear ISB transitions are apparent in the figure, with full widths at half maximum around 30% of the peak energy, consistent with our previous reports [2]. The energy at which the ISB should be observed is calculated by solving self-consistently the Schrödinger and Poisson equations to find the energies of the confined levels in the QW. Then, the ISB transition frequency is modified by the screening effect of the electrons, in the phenomenon called depolarization shift [2] [12]. The results are shown in the figures with vertical dotted lines.

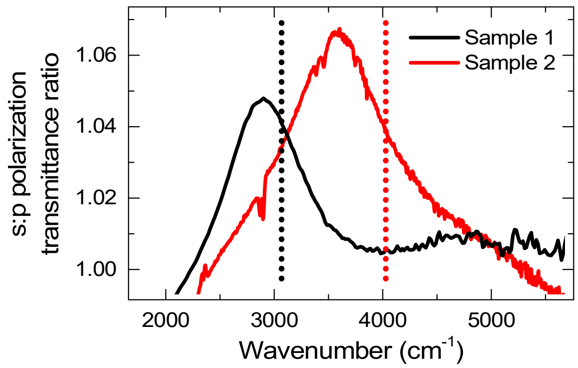


Figure 3. Ratio of the transmittance spectra taken under p and s polarizations at 50º degree of incidence of the incident light for the two samples. The dotted lines indicate the calculated wavenumber at which the ISB transition would be observed accounting for depolarization shift.

Once we know the photon energies absorbed by the ISB transitions, we can verify whether the mechanism described above (Figure 1) is actually happening. The angle of incidence is reduced to zero (i.e. normal incidence) and the transmittance spectra is recorded for light polarized perpendicular and parallel to the c axis. A plot of the transmittance ratio between the spectra taken when $\boldsymbol{E} \parallel c$ and $\boldsymbol{E} \perp c$ is shown in Figure 4. It is apparent from the figure that both samples are indeed absorbing light at the energy of the ISB transitions and, due to the way the ratio is taken (i.e. $\boldsymbol{E} \parallel c : \boldsymbol{E} \perp c$), it is also clear that the polarization sensitivity described in Figure 1 is indeed taking place.

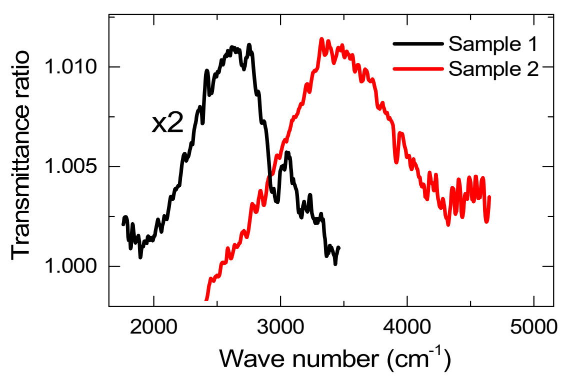


Figure 4. Ratio of the transmittance spectra taken at normal incidence when $\boldsymbol{E} \parallel c$ and $\boldsymbol{E} \perp c$ for both samples in the paper.

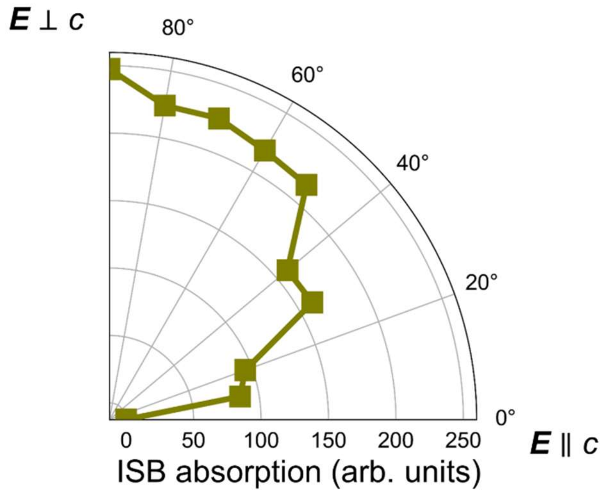


Figure 5. Integrated ISB absorption obtained from Sample 2 as a function of the polarization angle with respect to the c axis.

4. CONCLUSIONS

We have demonstrated that m-plane ZnO/MgZnO multiple QWs are capable of intersubband absorption when illuminated by infrared light at normal incidence, with the added feature of polarization sensitivity. This is due to the spontaneously occurring V-groove shape along the a-axis (i.e. across the c-axis) m-plane ZnO/MgZnO QWs feature. As a consequence of this morphology, normal incident light polarized perpendicular to the c-axis have a small component of the electric field which is perpendicular to the planes of the QWs, therefore fulfilling the selection rule for polarization in ISB transitions. If, on the contrary, the light is polarized parallel to the c-axis, the electric field of the electromagnetic wave is contained in the plane of the QWs and no ISB transitions are allowed, just as in regular, flat QWs. This mechanism gives this material system its polarization sensitivity.

ACKNOWLEDGEMENTS

This work was supported by the European Union's Horizon 2020 Research and Innovation Program under grant agreement No. 665107 (project ZOTERAC) and by the SpanishMinistry of Economy and Competitiveness (MINECO) through Project No. TEC2017-85912-C2-1-R. Part of the calculations performed here used the Aestimo package.

REFERENCES

[1] M. Belmoubarik, K. Ohtani and H. Ohno, "Intersubband transitions in ZnO multiple quantum wells," *Appl. Phys. Lett.,* vol. 92, p. 191906, 2008.

[2] M. Montes Bajo, J. Tamayo-Arriola, M. Hugues, J. M. Ulloa, N. Le Biavan, R. Peretti, F. H. Julien, J. Faist, J.-M. Chauveau and A. Hierro, "Multisubband Plasmons in Doped ZnO Quantum Wells," *Phys. Rev. Appl.,* vol. 10, p. 024005, 2018.

[3] N. Le Biavan, M. Hugues, M. Montes Bajo, J. Tamayo-Arriola, A. Jollivet, D. Lefebvre, Y. Cordier, B. Vinter, F.-H. Julien, A. Hierro and J.-M. Chauveau, "Homoepitaxy of non-polar

ZnO/(Zn,Mg)O multi-quantum wells: From a precise growth control to the observation of intersubband transitions," *Appl. Phys. Lett.,* vol. 111, p. 231903, 2017.

[4] A. Jollivet, B. Hinkov, S. Pirotta, H. Hoang, S. Derelle, J. Jaeck, M. Tchernycheva, R. Colombelli, A. Bousseksou, M. Hugues, N. Le Biavan, J. Tamayo-Arriola, M. Montes Bajo, L. Rigutti, A. Hierro, G. Strasser, J.-M. Chauveau and F. H. Julien, "Short infrared wavelength quantum cascade detectors based on m-plane ZnO/ZnMgO quantum wells," *Appl. Phys. Lett.,* vol. 113, p. 251104, 2018.

[5] H. Schneider and H. C. Liu, Quantum Well Infrared Photodetectors, Berlin: Springer, 2007.

[6] V. Apalkov, G. Ariyawansa, A. G. Unil Perera, M. Buchanan, Z. R. Wasilewski and H. C. Liu, "Polarization Sensitivity of Quantum Well Infrared Photodetector Coupled to a Metallic Diffraction Grid," *IEEE J. Quantum Electron.,* vol. 46, p. 877, 2010.

[7] A. Berurier and A. Nedelcu, "Optimization of light polarization sensitivity in QWIP detectors," *Infrared Phys. Technol,* vol. 59, p. 118, 2013.

[8] T. Antoni, A. Nedelcu, X. Marcadet, H. Facoetti and V. Berger, "High contrast polarization sensitive quantum well infrared photodetectors," *Appl. Phys. Lett.,* vol. 90, p. 201107, 2007.

[9] C. J. Chen, K. K. Choi, L. Rokhinson, W. H. Chang and D. C. Tsui, "Corrugated quantum well infrared photodetectors for polarization detection," *Appl. Phys. Lett.,* vol. 74, p. 862, 1999.

[10] E. Di Russo, L. Mancini, F. Moyon, S. Moldovan, J. Houard, F. H. Julien, M. Tchernycheva, J.-M. Chauveau, M. Hugues, G. Da Costa, I. Blum, W. Lefebvre, D. Blavette and L. Rigutti, "Three-dimensional atomic-scale investigation of ZnO-MgxZn1-xO m-plane heterostructures," *Appl. Phys. Lett.,* vol. 111, p. 032108, 2017.

[11] M. Montes Bajo, J. Tamayo-Arriola, N. Le Biavan, J. M. Ulloa, P. Vennéguès, D. Lefebvre, M. Hugues, J.-M. Chauveau and A. Hierro, "Breaking the Intersubband Selection Rules for Absorption with ZnO Quantum Wells: Light Polarization Sensitivity under Normal Incidence," *Phys. Rev. Appl.,* vol. 10, pp. 0340221-0340227, 2018.

[12] T. Ando, A. B. Fowler and F. Stern, "Electronic properties of two-dimensional systems," *Rev. Mod. Phys.,* vol. 54, pp. 437-672, 1982.