Characterization of low temperature InGaAs-InAlAs semiconductor photo mixers at 1.55 μ m wavelength illumination for terahertz generation and detection

I. Kostakis, D. Saeedkia, and M. Missous

Citation: *J. Appl. Phys.* **111**, 103105 (2012); doi: 10.1063/1.4719052

View online: <http://dx.doi.org/10.1063/1.4719052>

View Table of Contents: <http://jap.aip.org/resource/1/JAPIAU/v111/i10>

Published by the American Institute of Physics.

Related Articles

A simple analysis of interband absorption in quantum well structure of III-V ternary and quaternary semiconductors

J. Appl. Phys. **111**, 103104 (2012)

Indium incorporation and emission properties of nonpolar and semipolar InGaN quantum wells

Appl. Phys. Lett. **100**, 201108 (2012)

Dynamics of localized excitons in Ga_{0.69}In_{0.31}N_{0.015}As_{0.985}/GaAs quantum well: Experimental studies and Monte-Carlo simulations

Appl. Phys. Lett. **100**, 202105 (2012)

The contribution of quantum confinement to optical anisotropy of a-plane Cd_{0.06}Zn_{0.94}O/ZnO quantum wells

Appl. Phys. Lett. **100**, 171910 (2012)

Spatially modulated photoluminescence properties in dynamically strained GaAs/AlAs quantum wells by surface acoustic wave

Appl. Phys. Lett. **100**, 162109 (2012)

Additional information on J. Appl. Phys.

Journal Homepage: <http://jap.aip.org/>

Journal Information: http://jap.aip.org/about/about_the_journal

Top downloads: http://jap.aip.org/features/most_downloaded

Information for Authors: <http://jap.aip.org/authors>

ADVERTISEMENT

The advertisement features a green and yellow color scheme with abstract, flowing line patterns in the background. At the top, the 'AIP Advances' logo is displayed, with 'AIP' in blue and 'Advances' in green, accompanied by a series of orange dots. Below this, the text 'Special Topic Section: PHYSICS OF CANCER' is written in white, with 'PHYSICS OF CANCER' in a larger, bold font. At the bottom, the phrase 'Why cancer? Why physics?' is written in yellow, and a blue button with the text 'View Articles Now' is positioned on the right.

AIP Advances

Special Topic Section:
PHYSICS OF CANCER

Why cancer? Why physics? [View Articles Now](#)

Characterization of low temperature InGaAs-InAlAs semiconductor photo mixers at 1.55 μm wavelength illumination for terahertz generation and detection

I. Kostakis,¹ D. Saeedkia,^{2,3} and M. Missous¹

¹*School of Electrical and Electronic Engineering, University of Manchester, Sackville Street, Manchester M13 9PL, United Kingdom*

²*T-Era Consulting, Waterloo, Ontario N2V 2Y4, Canada*

³*TeTechS, Inc., Waterloo, Ontario N2V 2Y4, Canada*

(Received 1 February 2012; accepted 10 April 2012; published online 21 May 2012)

The structural, optical, and electrical properties of undoped and Be doped lattice matched InGaAs-InAlAs multiple quantum well structures, grown by molecular beam epitaxy (MBE) at low ($\sim 250^\circ\text{C}$) and normal ($\sim 450^\circ\text{C}$) growth temperatures, have been investigated in detail. Double crystal x-ray diffraction studies showed that the thickness of the low temperature (LT) grown quantum well (QW) layers decrease with post growth annealing, while the normal temperature grown QW layers retain their initial thickness. This behaviour is associated with the As precipitation and is the first evidence and report of a direct observation of this phenomenon in LT InGaAs-InAlAs QWs. Room temperature photoluminescence (PL) measurements revealed signs of optical activities in the LT undoped and lower doped structures suggesting that the native defects in LT InGaAs-InAlAs are not sufficient to completely inhibit band to band recombination. Optimal combination of doping, including a modulation doped structure, and post growth annealing temperature results in materials with sub-picoseconds lifetimes (< 200 fs) and a resistivity of $\sim 10^7 \Omega/\text{sq}$, which is a high value for this material. The results imply the possibility of fabricating efficient photo-mixers operating at the telecom wavelength of 1.55 μm for THz imaging or other optoelectronic applications. © 2012 American Institute of Physics. [<http://dx.doi.org/10.1063/1.4719052>]

I. INTRODUCTION

The potential of THz radiation in various applications such as imaging and spectroscopy has made it very popular recently leading to a very active research area with many scientific publications. This recent interest is forcing researchers to develop sources that are able to emit THz radiation with high efficiency and thus high output power levels. Among all existing THz sources the most widely used ones belong to the innovative field of THz optoelectronics and are laser driven sources. These sources are based on the frequency down conversion from the optical region and rely on semiconductor photoconductive (PC) switches, a concept pioneered by Auston¹ and Lee.² There are two techniques to generate THz radiation in the above semiconductor-based approach. The first one produces broadband pulsed THz radiation and is based on femtosecond pulsed lasers, such as Ti:sapphire, driving PC switches.^{3,4} The second one produces narrowband continuous wave (CW) THz radiation and is based on photomixing two CW lasers in a photoconductor (or photomixer as it is called in that case).⁵ The difference in frequency between the two lasers is tuned to the THz region. The material requirements for efficient THz emitters and detectors are high resistivity, sub picosecond carrier lifetime and high electron mobility.^{6–8} These characteristics are stricter in the case of the photomixers. Although a great deal of improvement in the growth of high speed III–V optoelectronic devices and solid state lasers has happened in the last

decade, the obtained output THz power is still not in the desired levels. The maximum output power is usually limited by a thermal damage threshold which then sets the upper limit on power generation.

At present the most successful photomixer is the low temperature GaAs (LT GaAs).⁹ The reason is that it meets all material requirements due to the formation of deep energy levels in the middle of the energy band gap of the semiconductor. These energy levels arise from the formation of point defects during the growth at low temperatures, i.e., $\leq 250^\circ\text{C}$, using the molecular beam epitaxy (MBE) technique. Although LT GaAs remains the most intensively studied material for ultrafast optoelectronic applications, its rather large band gap energy imposes certain limits on lasers that can be used which on the whole tend to be bulky and very expensive components. The search for lower cost solutions led to the development of materials with smaller energy band gaps than the LT GaAs. The LT $\text{In}_{0.3}\text{Ga}_{0.7}\text{As}$ lattice mismatch on GaAs provides desired characteristics and can reduce the system cost as it can be used with neodymium (Nd) based lasers ($\sim 1.06 \mu\text{m}$).^{10,11} However, the most desirable system comprises photomixers combined with optically fibre coupled communication lasers operating at the 1.3 or 1.55 μm wavelength. This opens up the way to a wealth of readily available active and passive optical components. The challenge at hand thus is the synthesis of materials that combine the desirable properties of the LT GaAs while at the same time are able to be excited at the practical and cost

effective telecommunication wavelengths of $1.3\ \mu\text{m}$ and $1.55\ \mu\text{m}$. The commercialisation of portable $1.55\ \mu\text{m}$ THz imaging systems has recently begun.^{12,13}

In this work, we concentrate on the characterisation of a series of low temperature lattice matched $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ – $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ multiple quantum well structures. The key findings have led to materials, whose lifetimes are $<1\ \text{ps}$ and resistivities an order of magnitude higher than the best reported¹³ to date in this material system creating conditions for the fabrication of efficient and powerful THz components.

II. SAMPLES—EXPERIMENTS

A series of lattice matched LT InGaAs – InAlAs layers were grown by MBE on semi-insulating, iron-doped InP substrates. The samples were grown using a RIBER V90H and RIBER V100 MBE systems (with samples grown on these systems having acronyms “VMBE” and “XMBE” respectively). The initial structures were inspired from designs by Chen *et al.*¹⁴ The “VMBE” samples consist of a $900\ \text{\AA}$ InAlAs buffer layer grown at 520°C followed by 50 periods of InGaAs ($120\ \text{\AA}$) and InAlAs ($90\ \text{\AA}$) superlattice structure grown at a nominal temperature of 220 – 230°C . On top of the superlattice structure, a $120\ \text{\AA}$ InGaAs cap layer was grown at the same nominal low temperature. The “XMBE” samples consist of a $1000\ \text{\AA}$ InAlAs buffer layer grown at 520°C on top of which a superlattice structure of InGaAs ($140\ \text{\AA}$) and InAlAs ($200\ \text{\AA}$) was repeated 50 times and grown at a nominal temperature of 220 – 230°C . The set of the “VMBE” samples contained one control (all layers were grown at normal conditions), one undoped and four samples with beryllium (Be) doping of $2.5 \times 10^{17}\ \text{cm}^{-3}$, $6.5 \times 10^{17}\ \text{cm}^{-3}$, $1.5 \times 10^{18}\ \text{cm}^{-3}$, and $2 \times 10^{18}\ \text{cm}^{-3}$ throughout the structure. The “XMBE” set contained two samples with Be doping of $1.5 \times 10^{18}\ \text{cm}^{-3}$ and $2 \times 10^{18}\ \text{cm}^{-3}$ in the quantum well layers only and one sample with Be doping of $2 \times 10^{18}\ \text{cm}^{-3}$ in the barrier layers only (modulation doping). Following growth, both “VMBE” and “XMBE” samples were annealed *ex situ* at temperatures between 300 and 600°C in a rapid thermal annealer (RTA) in a nitrogen atmosphere and in contact with a semi-insulating GaAs wafer to passivate the surface and inhibit arsenic loss. The anneal duration was 10 min, as this was found to be the optimal timing for achieving full equilibrium defect concentrations.

The structure of each sample was characterised using a Bede QC200 double crystal x-ray diffraction (DCXRD) system with a $1.54056\ \text{\AA}$ x-ray source of random polarisation. An InP substrate was used as a reference crystal with all measurements using the (004) reflection plane geometry. The photoluminescence (PL) measurements were performed at room temperature using an Accent RPM2000 system with an $8\ \text{mW}$ laser ($532\ \text{nm}$) source and an InGaAs array detector. The mid infrared absorption measurements were performed at room temperature using an Ocean Optics LS1 tungsten halogen light source and an Ocean Optics NIR 256–2.1 extended InGaAs detector. The transport properties were obtained using Hall effect measurements at room temperature based on the Van Der Pauw method. A customised

set-up consisting of a Keithley 196 system DMM, Keithley 705 scanner, Keithley 220 Programmable current source, and a Keithley 485 Autoranging picoammeter was used for the measurements. With this set-up current as low as $1\ \text{nA}$ could be supplied to the highly resistive samples. Carrier dynamic measurements were performed using an infrared pump-probe system. The laser used was a FemtoFiber FFS short pulse laser from Toptica Photonics AG with $100\ \text{fs}$ pulse duration, $86\ \text{MHz}$ pulse repetition rate, $1550\ \text{nm}$ working wavelength, $100\ \text{mW}$ pump beam average power, and $5\ \text{mW}$ probe beam average power.

III. RESULTS AND DISCUSSIONS

A. DCXRD measurements

X-ray diffraction was used to examine the defects incorporated during the low temperature growth and the changes induced by the post growth annealing process. Fig. 1 shows the rocking curves for the control and the LT-undoped samples as a function of post growth annealing.

In a comparison between the sample grown at normal conditions (VMBE1993) and the LT undoped sample (VMBE2001), it is clear from the rocking curve spectra that there is a sizeable movement of the quantum well (QW) satellite peaks in the case of the undoped sample as the annealing temperature is increased. The latter corresponds to a decrease in the QW thickness, which we associate with a decrease of the lattice constant of the LT material and subsequent formation of arsenic precipitates. This is the first evidence and report of a direct observation of this phenomenon in LT InGaAs – InAlAs superlattices. A similar behaviour was observed in all LT “VMBE” and “XMBE” samples studied suggesting that the fundamental point defects behaviour is the same in all samples and is unaffected by the Be doping profile. As the Be atoms sit preferentially on Ga sites one would have expected competition from arsenic anti-sites for this but this does not seem to happen, at least for the Be doping levels used here.

FIG. 1. Control and LT-undoped rocking curves for the as-grown and annealed (350 – 600°C) samples. The rocking curves are referenced to the substrate peak. The inset shows the zoomed in area of the 0th order QW satellite peak for the LT-Undoped sample. The shift in the peak position is clearly seen and the arrow indicates the trend with annealing temperature.

B. Photoluminescence

The room temperature PL measurements provided information about the optical activity in these materials. The sample grown at normal conditions (VMBE1993) exhibited a strong light emission at around $1.55\ \mu\text{m}$, which corresponds to the radiative recombination between the electrons and heavy holes of the first transition level within the InGaAs QW. The intensity of the emitted photons is reduced with the increase in the post growth annealing temperature as can be seen in Fig. 2. The inset shows the PL spectrum and the post growth annealing effect for the LT undoped sample. Unlike LT GaAs, both the LT undoped (VMBE2001) and LT low doped (VMBE1995) samples in our study showed signs of optical activities implying that the native defects in LT InGaAs-InAlAs are not sufficient to completely inhibit band to band recombination. The post growth annealing effect was similar to the one in the control sample as the photon emission reduced and eventually eliminated with the increase in the annealing temperature.

By contrast, the recombination processes became nonradiative with the increase in the Be doping concentration and remained unaffected by the post growth annealing. Such behaviour was also the case for the “XMBE” samples. Fig. 3 illustrates that not PL emission could be seen for the doped samples at any annealing temperature.

C. Mid infrared absorption

The measured room temperature absorption spectrum of the control MQW sample grown under normal conditions is shown in Fig. 4(a). The graph clearly shows the main attribute of the QWs, which is the quantisation of the energy levels. Excitonic transitions up to the second subband energy level are visible and well defined indicating a high crystal quality. The heavy- and light-hole resonances are seen at the first energy level (ground state) as well as the heavy-hole resonance at the second level. The “VMBE” LT undoped sample retained the good crystallinity, while the heavily doped “VMBE” LT sample exhibited a crystal alteration due to the

FIG. 2. PL spectra as a function of annealing temperature for the control sample (VMBE1993). A strong PL signal is shown at $1.55\ \mu\text{m}$ which decreases as the annealing temperature is increased. The inset shows the PL response of the LT undoped sample (VMBE2001).

FIG. 3. Noise spectra as a function of annealing for the samples doped throughout the structure (VMBE) and the samples with modulated doping (XMBE).

heavy doping concentration and the formation of Be-As complexes. The consequence of this is the fluctuation of the quantisation of energy and thus more abrupt transitions as well as a blue-shift of the band-edge resonances as shown in Fig. 4(b), without however compromising the absorbance at $1.55\ \mu\text{m}$.

Doping with Be in either the QW only or in the barrier only resulted in a better optical behaviour. As a consequence both heavy- and light-hole resonances of the first two subband energy levels were visible in the absorption spectrum, Fig. 5(a). Considering the total thickness of the layers that contribute to the absorption at the $1.55\ \mu\text{m}$ wavelength (LT InGaAs), the absorption coefficient is found to be higher in the sample doped in the barrier layers only as can be seen in Fig. 5(b).

In any case, the post growth annealing did not affect the absorbance and the absorption coefficient retained the same levels in contrast to what has been reported in a previous study.¹⁵

FIG. 4. Absorption spectra of InGaAs/InAlAs MQWs at room temperature for the (a) normal temperature growth VMBE as-grown sample and (b) LT VMBE undoped and LT VMBE heavily doped as-grown samples.

FIG. 5. (a) Room temperature absorption spectrum for the heavily doped XMBE as-grown samples. (b) Relevant absorption coefficient. The absorption coefficient was calculated using the total well thickness ($7000 \text{ \AA}$).

D. Electrical properties

The experimental Hall data for the VMBE samples are illustrated in Fig. 6. The data revealed that although there is an undeniable re-ordering and restructuring of the excess arsenic atoms during the post growth annealing, the electrical properties of the “VMBE” LT undoped sample remained unaffected. The latter is in contrast to the case of the LT GaAs, where the annealing reduces the carrier concentration and thus increases the resistivity. Unlike what has been reported in a previous study,¹⁶ the incorporation of various levels of Be result in a decrease of the background concentration levels (always n-type). The compromise of the reduced carrier concentration, however, is the drop in the mobility which is almost six times lower in the heavily doped structure. Furthermore, the carrier concentration of the doped samples is reduced significantly after annealing, particularly three orders of magnitude in the case of the most heavily doped sample. On the other hand, the mobility is not affected as it retains the same levels. The latter implies that the resistivity of the material can be increased by performing

post growth annealing without compromising the mobility. It is well established that the transport properties in the quantum well can be strongly affected by various scattering mechanisms such as background charged impurities, remote ionised dopants, optical phonons, interface roughness, and alloy disorder.^{17–19} Considering the mobility behaviour in the Hall data the conclusion that can be made here is that the remote dopants scattering contributes mostly to the drop of the mobility making it the dominant scattering mechanism for this material system.

An exact similar behaviour was observed in the samples with the modulated doping (i.e., doping in the barrier only) or in the QW layer only. The experimental results are shown in Fig. 7. Similarly to the “VMBE” samples, the dopants scattering dominates in the drop of the mobility for the highly doped samples. The increase of the barrier layer thickness in conjunction with the modulated doping had as a consequence the spatial separation of the electrons confined in the well and the donor impurities. The latter results in the scattering strength decrease and therefore in mobility enhancement, as expected.^{18,20,21}

The sheet resistances of the samples LT undoped (VMBE2001), heavily doped throughout the structure (VMBE2094), heavily doped in the QW layer only (XMBE236), and heavily doped in the barrier layer only (XMBE248) are shown in Fig. 8. The graph depicts the resistivity for the as-grown samples and the samples annealed at the optimal temperatures, taking into account carrier concentration and mobility. The values are compared with those from a control LT GaAs sample. The sample VMBE2094 exhibits one order of magnitude higher sheet resistance than the best reported in the literature¹³ and two orders of magnitudes lower than that of the LT GaAs. The consequence of the carrier concentration drop as the annealing temperature is increased can be seen in the graph by comparing the resistivity values for the as-grown and the upper annealing temperatures. The superiority of the doping throughout the structure to the modulated doping in the increase of the resistivity is clear in the graph. The effect of the post growth annealing in the electrical properties is in a good agreement

FIG. 6. Hall effect results for the VMBE samples showing the effect of the Be incorporation and the post growth annealing in the carrier concentration and mobility.

FIG. 7. Hall effect results for the XMBE samples showing the effect of the Be incorporation and the post growth annealing in the carrier concentration and mobility.

FIG. 8. Sheet resistance as a function of annealing for the LT undoped and heavily doped samples compared with the values of the LT GaAs and the highest reported in the literature.

with what has been reported in the past for the same material system.^{14,22}

E. Carrier dynamics

Carrier dynamics for the Be doped samples were measured using a pump-probe measurement setup at 1.55 μm wavelength range. In such a setup, both pump and probe beams are focused on the sample in the same spot, and the reflected probe power is measured by an InGaAs photodiode detector. The probe pulse is a delayed version of the pump pulse, where the time delay is controlled and changed by moving a retro-reflector mirror on a motorised translation stage. The measured signal by the detector is proportional to the change in the reflectivity of the sample due to the free carrier generation by the pump beam. The carrier lifetime can then be calculated by taking the single exponential best fit line in the plotted graphs of the experimental results. The

FIG. 9. Carrier dynamics for the three samples that provided the desired optical and electrical characteristics for prospective THz emitters and detectors.

FIG. 10. Carrier lifetime as a function of annealing temperature for the low doped and heavily doped VMBE samples. Note the different time scales used in the figure.

carrier lifetimes for the samples that exhibited the desired resistivity and mobility values are depicted in Fig. 9. Lifetimes as short as 113 fs are derived, which are amongst the shortest ever reported for this material system.

A further study of the carrier dynamics in the LT InGaAs-InAlAs MQW structures can be seen in Fig. 10. In the low doped case, the very long carrier lifetime is related to the existence of a long-lived residual photoconductivity¹⁴ and the drop after annealing to the compensation behaviour of the Be-As defects and to the As precipitation. On the other hand, the fast decay time in the heavily doped case implies that the formation of the Be-As complex and its related defects dominate the recombination process making the carrier lifetime a strong function of the doping level. The further decrease of the carrier lifetime with annealing implies that the As precipitation enhances the ultrafast photoresponse but does not reduce the defect concentration, which is in contrast to what has been reported in previous studies^{15,22} or indeed in LT GaAs materials.⁸

This data is also consistent with the PL response. The low doped sample exhibited PL emission when the lifetime was very long, while the emission was eliminated when the lifetime was in the sub picosecond regime. Therefore, a peak in the PL spectrum is an indication of long carrier lifetimes.

IV. CONCLUSION

Structural, optical and electrical properties of Be doped InGaAs-InAlAs MQW structures grown at low temperature were investigated in detail. The reduction in the QW thickness during the post growth annealing, which was clearly indicated in the DCXRD rocking curve as a sizeable movement of the QW satellite peak was associated with excess As precipitation. The former was also found to be unaffected by Be doping as similar behaviour was observed in all the samples studied. The incorporation of Be atoms in conjunction with the post growth annealing resulted in a significant improvement in the carrier lifetime and resistivity characteristics of the structures.

The study in our materials indicates the possibility of fabricating photomixers operating at the 1.55 μm by using

the heavily doped samples VMBE2094 and XMBE248. The ultra short carrier lifetime (118 fs), the high sheet resistance ($\sim 10^7 \Omega/\text{sq}$) and the relatively good mobility ($\sim 500 \text{ cm}^2/\text{Vs}$) of sample VMBE2094 makes it preferable for THz detector as the high dark resistivity reduces the detected noise. On the other hand, the ultra short carrier lifetime (113 fs), the high mobility ($\sim 1800 \text{ cm}^2/\text{Vs}$) and the relatively high sheet resistance ($\sim 10^5 \Omega/\text{sq}$) of sample XMBE248 makes it preferable for THz emitter as the high electron mobility enhances the emitted THz power. Antenna structures made from these materials are being evaluated in THz systems.

ACKNOWLEDGMENTS

We gratefully acknowledge financial support from the UK's Engineering and Physical Sciences Research Council and the use of the THz Photonics lab of the University of Waterloo. One of us (IK) is also grateful to Scimus Solutions Ltd for financial support.

- ¹D. Auston, "Picosecond optoelectronic switching and gating in silicon," *Appl. Phys. Lett.* **26**(3), 101 (1975).
- ²C. Lee, "Picosecond optoelectronic switching in GaAs," *Appl. Phys. Lett.* **30**(2), 84 (1977).
- ³Z. Jiang and X.-C. Zhang, "Terahertz imaging via electrooptic effect," *IEEE Trans. Microwave Theory Tech.* **47**, 2644 (1999).
- ⁴Q. Wu, T. D. Hewitt, and X.-C. Zhang, "Two dimensional electro-optic imaging of THz beams," *Appl. Phys. Lett.* **69**, 1026 (1996).
- ⁵E. R. Brown, K. A. McIntosh, K. B. Nichols, and C. L. Dennis, "Photomixing up to 3.8 THz in low temperature-grown GaAs," *Appl. Phys. Lett.* **66**, 285 (1995).
- ⁶L. Duvillaret, F. Garet, J. Roux, and J. Coutaz, "Analytical modelling and optimization of terahertz time-domain spectroscopy experiments using photoswitches as antennas," *IEEE J. Sel. Top. Quantum Electron.* **7**(4), 615 (2001).
- ⁷P. Upadhyay, W. Fan, A. Burnett, J. Cunningham, A. Davies, E. Linfield, J. Hughes, E. Camus, M. Johnston, and H. Beere, "Excitation-density-dependent generation of broadband terahertz radiation in an asymmetrically exited photoconductive antenna," *Opt. Lett.* **32**(16), 2297 (2007).
- ⁸I. Gregory, C. Baker, W. R. Tribe, M. Evans, H. Beere, E. Linfield, A. Davies, and M. Missous, "High resistivity annealed low-temperature GaAs with 100 fs lifetimes," *Appl. Phys. Lett.* **83**, 4199 (2003).

- ⁹P. Kordos, F. Ruders, M. Marso, and A. Forster, "Properties of LT GaAs for photomixing up to THz frequencies," in *Optoelectronic and Microelectronic Materials and Devices Proceedings* (Institute of Thin Film and Ion Technology, Research Centre Jülich, Germany, 1996), p. 71–74.
- ¹⁰C. Baker, I. Gregory, W. Tribe, I. Bradley, M. Evans, E. Linfield, and M. Missous, "Highly resistive annealed low-temperature-grown InGaAs with sub-fs 500 carrier lifetimes," *Appl. Phys. Lett.* **85**(21), 4965 (2004).
- ¹¹C. Baker, I. Gregory, W. Tribe, I. Bradley, M. Evans, M. Withers, P. Taday, V. Wallace, E. Linfield, A. Davies, and M. Missous, "Terahertz pulsed imaging with 1.06 μm laser excitation," *Appl. Phys. Lett.* **83**(20), 4113 (2003).
- ¹²S. Preu, G. H. Dohler, S. Malzer, L. J. Wang, and A. C. Gossard, "Tunable, continuous-wave terahertz photomixer sources and applications," *J. Appl. Phys.* **109**, 061301 (2011).
- ¹³B. Sartorius, H. Roehle, H. Kunzel, J. Bottcher, M. Schlak, D. Stanze, H. Venghaus, and M. Schell, "All fiber terahertz time domain spectrometer operating at 1.5 μm telecom wavelengths," *Opt. Express* **16**(13), 9565 (2008).
- ¹⁴Y. Chen, S. Prabhu, S. Ralph, and D. McInturf, "Trapping and recombination dynamics of low temperature-grown InGaAs/InAlAs multiple quantum wells," *Appl. Phys. Lett.* **72**(4), 439 (1998).
- ¹⁵P. Juodawlkis, D. McInturf, and S. Ralph, "Ultrafast carrier dynamics and optical nonlinearities of low-temperature-grown InGaAs/InAlAs multiple quantum wells," *Appl. Phys. Lett.* **69**(26), 4062 (1996).
- ¹⁶R. Takahashi, Y. Kawamura, T. Kagawa, and H. Iwamura, "Ultrafast 1.55- μm photoresponses in low-temperature-grown InGaAs/InAlAs quantum wells," *Appl. Phys. Lett.* **65**(14), 1790 (1994).
- ¹⁷C. Emeleus, T. Whall, D. Smith, R. Kubiak, E. Parker, and M. Kearney, "Scattering mechanisms affecting hole transport in remote-doped Si/SiGe heterostructures," *J. Appl. Phys.* **73**(8), 3852 (1993).
- ¹⁸D. Laroche, S. Das Dharma, G. Gervais, M. P. Lilly, and J. L. Reno, "Scattering mechanism in modulation-doped shallow two-dimensional electron gases," *Appl. Phys. Lett.* **96**, 162112 (2010).
- ¹⁹E. H. Hwang and S. Das Sarma, "Limit to two-dimensional mobility in modulation-doped GaAs quantum structures: How to achieve a mobility of 100 million," *Phys. Rev. B* **77**, 235437 (2008).
- ²⁰R. Dingle, H. L. Stormer, A. C. Gossard, and W. Wiegmann, "Electron mobilities in modulation-doped semiconductor heterojunction superlattices," *Appl. Phys. Lett.* **33**(7), 665 (1978).
- ²¹T. Tsuchiya and T. Ando, "Mobility enhancement in quantum wells by electronic-state modulation," *Phys. Rev. B* **48**(7), 4599 (1992).
- ²²H. Kuenzel, J. Boettcher, K. Biermann, H. Hensel, H. Roehle, and B. Sartorius, "Low temperature MBE-grown In(Ga,Al)As/InP structures for 1.55 μm THz photoconductive antenna applications," in *20th International Conference on Indium Phosphide and Related Materials, IPRM 2008* (IEEE Lasers and Electro-Optics Society, IEEE Electron Devices Society, 2008), p. 1–4.