APPLIED PHYSICS LETTERS **94**, 031903 (2009)

Contactless electroreflectance of GaInNAsSb/GaNAs/GaAs quantum wells emitting at 1.5–1.65 μm: Broadening of the fundamental transition

R. Kudrawiec,[1,a)] P. Poloczek,[1] J. Misiewicz,[1] H. P. Bae,[2] T. Sarmiento,[2] S. R. Bank,[2]
H. B. Yuen,[2] M. A. Wistey,[2] and James S. Harris, Jr.[2]
[1]*Institute of Physics, Wrocław University of Technology, Wybrzeze Wyspianskiego 27,*
50-370 Wrocław, Poland
[2]*Department of Electrical Engineering, Solid State and Photonics Laboratory, Via Ortega,*
Stanford University, Stanford, California 94305-4075, USA

(Received 22 October 2008; accepted 31 December 2008; published online 22 January 2009)

Contactless electroreflectance (CER) has been applied to study the broadening of the fundamental transition for GaInNAsSb/GaNAs/GaAs quantum wells (QWs) obtained at various growth and annealing conditions. It has been observed that CER resonances are about 50% narrower for QWs grown at lower group V fluxes and annealed at lower temperatures (660–720 °C) and longer time (30–60 min) than those previously considered optimal (~760 °C and ~60 s). The long annealing can be partially realized *in situ* during (and/or after) the growth of the upper part of the laser structure instead the *ex situ* short-time annealing, where the laser structure can unintentionally be overannealed very easily. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3073718]

The dilute nitrides are very attractive materials for low-cost GaAs-based laser diodes operating in the 1.3–1.55 μm optical fiber windows.[1,2] Recently, high-quality 1.55 μm lasers were achieved using a GaInNAsSb/GaNAs quantum well (QW) as the active region.[3,4] This was enabled by the significant improvement in GaInNAs quality through the incorporation of antimony, careful optimization of the growth conditions (especially the growth temperature), as well as postgrowth treatment by annealing (i.e., usually the *ex situ* annealing).[2,3]

In general, annealing has been employed in dilute nitrides as a standard process to remove as-grown defects and improve material quality. However, the optimal annealing conditions can vary with the content of dilute nitrides and are difficult to predict for unexplored dilute nitrides. Therefore, substantial attention was recently focused on experimental investigations of optimal annealing conditions for various dilute nitrides and quantum systems containing dilute nitrides.[5–10] It has been observed that the budget of annealing (the thermal energy which can be absorbed by the material without its degradation) is limited and some material degradations appear for samples annealed for too long time (i.e., overannealed samples). This time depends on the annealing temperature (i.e., shorter for higher annealing temperatures); however, it is possible to exhaust the thermal budget, even for low annealing temperatures if the annealing time is too long. This issue is very important for complex optoelectronic devices containing dilute nitrides since the optimal growth temperature for dilute nitrides is usually much lower than the optimal growth temperature for other parts of optoelectronic devices, which are grown after the growth of QW region (i.e., the upper cladding in edge-emitting lasers or the top distributed Bragg reflector in vertical cavity surface emitting lasers).[10] It means that the GaInNAsSb/GaNAs QW is subjected to hours of *in situ* annealing at a temperature higher than the optimal QW growth temperature and therefore annealing studies of dilute nitrides must be conducted with consideration of this inevitable *in situ* annealing.[8]

Recently, it has been shown that the quality of GaInNAsSb/GaNAs QW system can be improved by postgrowth annealing at much lower temperatures[11] than the previous annealing temperatures.[2,3] It means that the manipulation of the annealing conditions within the budget of annealing is still a promising way to the optimization of GaInNAsSb laser performance, especially that the annealing process can be partially conducted during the growth of the upper part of optoelectronic structures. A better understanding of the origin of photoluminescence (PL) improvement in GaInNAsSb/GaNAs system during the annealing is very interesting from the viewpoint of future optimization of long wavelength lasers based on this material system. In this context, it is interesting to investigate GaInNAsSb/GaNAs QW by other experimental techniques than PL. In this work we applied contactless electroreflectance (CER) to study the quality of two generations of GaInNAsSb lasers grown and annealed at various conditions: (i) the previous generation of GaInNAsSb lasers grown at 20X V-to-III flux ratio at 440 °C and annealed at high temperatures (760 °C) for short time (10–120 s),[3] (ii) the present generation of GaInNAsSb lasers grown at lower V-to-III flux ratio (11X) at 440 °C and annealed at lower temperatures (660–720 °C) for longer time (10–60 min).[11]

So far, electromodulation spectroscopy (photoreflectance and CER) was mostly used to investigate the band structure for as-grown GaInNAsSb QWs,[12–14] including GaInNAsSb/GaNAs/GaAs laser structures.[12,14] This technique, due to its absorptionlike character, is insensitive to point defects (nonradiative centers) unlike to PL where the intensity is directly sensitive to nonradiative centers. However, the broadening of CER resonances is very sensitive to energy gap fluctuations, which influence carrier localization and quantum efficiency of PL. Recently, it has been shown that the broadening of CER resonance is also very sensitive to atom segregation in GaInAs/GaAs QWs.[15] Therefore, the investigation of the broadening parameter for the fundamental QW transition in GaInNAsSb/GaNAs/GaAs structures is a good method to

---

[a)] Electronic mail: robert.kudrawiec@pwr.wroc.pl.

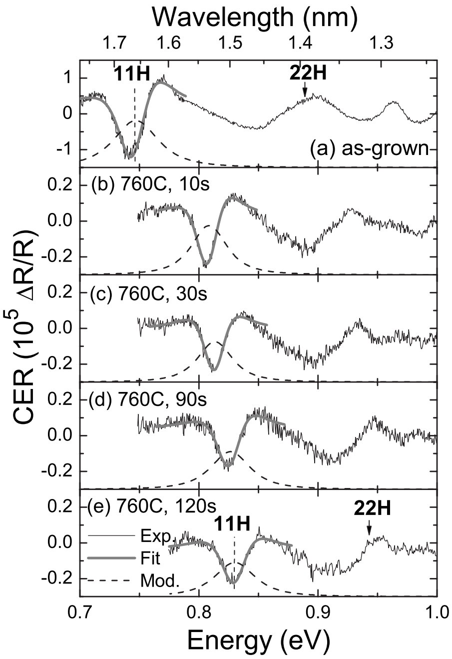

FIG. 1. Room temperature CER spectra in the vicinity of the ground state transition for GaInNAsSb/GaNAs QWs grown at 20X V-to-III ratio in BEP and annealed at 760 °C for various time ranges.

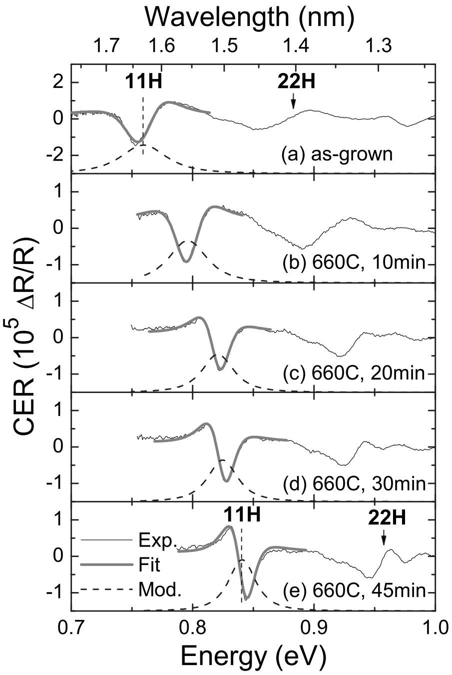

FIG. 2. Room temperature CER spectra in the vicinity of the ground state transition for GaInNAsSb/GaNAs QWs grown at 11X V-to-III ratio in BEP and annealed at 660 °C for various time ranges.

evaluate the potential homogeneity of this system.

Three sets of GaInNAsSb laser structures used for this study were grown by solid-source molecular beam epitaxy on *n*-type (001) GaAs substrates. The first generation of GaInNAsSb lasers is represented by GaInNAsSb/GaNAs QWs grown at the 20X V-to-III ratio in beam-equivalent pressure (BEP) and annealed at 760 °C in the time range of 10–120 s (set A), see remaining growth and annealing details in Ref. 3. The second generation of GaInNAsSb lasers is represented by GaInNAsSb/GaNAs QWs grown at the 11X V-to-III ratio in BEP and annealed at 660 and 720 °C in the time range of 10–120 min (set B1 and B2, respectively).[11] For the three sets of samples the active region was nominally a single 70 Å GaInNAsSb QW surrounded on either side by 200 Å GaNAs barriers grown at 440 °C. The active region was grown upon a 3000 Å GaAs buffer and capped with 500 Å of GaAs grown at 580 °C. The experimental setup used to measure the CER spectra is described in detail in Ref. 16.

Figures 1–3 show CER spectra for as-grown and annealed GaInNAsSb/GaNAs QW samples from sets A (previous generation of GaInNAsSb lasers), B1, and B2 (present generation of GaInNAsSb lasers), respectively. The identification of CER resonances was possible on the basis of the calculations performed in the framework of the effective mass approximation. The notation *klH* denotes the transition between the *k*th heavy-hole valence subband and the *l*th conduction subband. Relevant details of these calculations are discussed in our previous papers.[12–14] CER resonances, which are observed for the as-grown sample from set A, were analyzed in details in Ref. 14. The same optical transitions are observed for the as-grown sample from sets B1 and B2. In the case of annealed samples, all the optical transitions shift to blue due to the well known effect of annealing-induced blueshift of energy gap for dilute nitrides[6,17–20] and atom interdiffusion across QW interfaces.[20] In addition, a narrowing of CER resonances is clearly visible in Figs. 1–3. This narrowing is the subject of this paper. The blueshift of optical transitions is not discussed in this work since this issue was analyzed in many previous papers. In order to extract the broadening of CER resonance from the spectra in Figs. 1–3, the standard fitting procedure assuming Lorentzian lineshape[21] has been applied, see details in Refs. 12–14.

Figure 4 shows the broadening parameter of 11*H* transition for GaInNAsSb/GaNAs QW samples from sets A, B1, and B2, respectively. First, it is visible that the broadening parameter for as-grown samples from the previous and

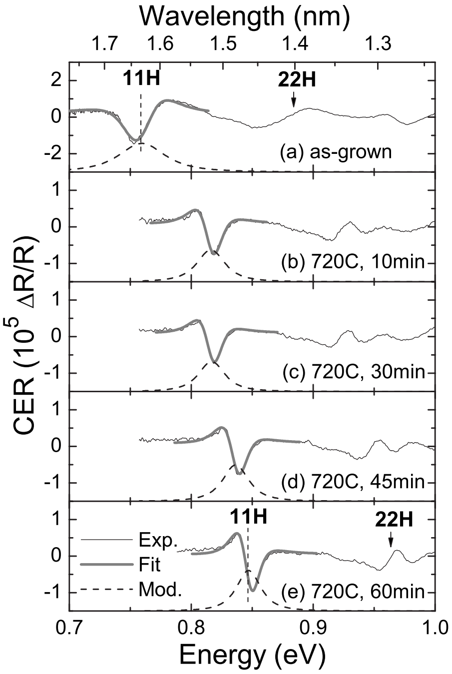

FIG. 3. Room temperature CER spectra in the vicinity of the ground state transition for GaInNAsSb/GaNAs QWs grown at 11X V-to-III ratio in BEP and annealed at 720 °C for various time ranges.

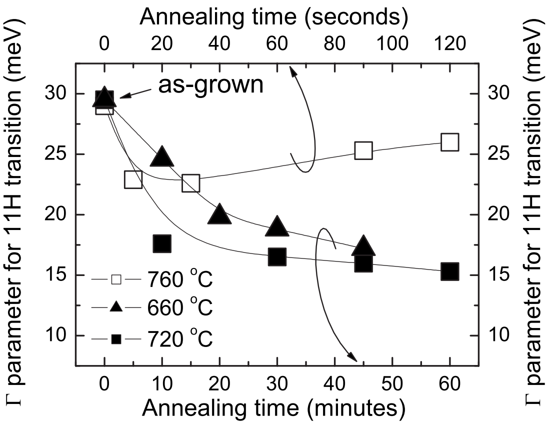

FIG. 4. Γ parameter (broadening parameter) for the $11H$ transition.

present generation of GaInNAsSb/GaNAs QWs is the same within the experimental error. Therefore, the quality of as-grown material for the two generations of GaInNAsSb lasers is comparable. The broadening parameter decreases after annealing for the three sets of samples but this decrease is different for the three series of samples. In the case of samples annealed at high temperatures for a short time, the narrowest CER resonance is observed for an annealing time of $\sim$10–20 s. For longer annealing time, the broadening parameter starts to increase, which means deterioration of material quality (strong atom interdiffusion across QW interfaces leading to stronger inhomogeneity in QW profile). For samples annealed at 660 and 720 °C, a continuous decrease in the broadening parameter is observed in this range of annealing time. In addition, it is visible that the slope of Γ decrease is weaker for the set of samples annealed at lower temperatures (i.e., 660 °C). For samples annealed at 720 °C, very narrow CER resonance is observed just after 10 min of annealing. The narrowest CER resonance has been observed for GaInNAsSb/GaNAs QWs annealed at 720 °C for 60 min. It is worth noting that such narrow CER (or photoreflectance) transitions have never been observed for dilute nitrides in this spectral range. In the case of GaInNAs(Sb) alloys, it has been many times shown that different nitrogen nearest neighbor-environments lead to various energy gaps.[6,17–20] The presence of various nitrogen environments inside GaInNAs(Sb) can be manifested by individual resonances in CER (photoreflectance) spectra or high broadening of $11H$ transition.[17–20] The observation of very narrow $11H$ transition in CER spectra is an evidence for the dominance of a one nitrogen nearest-neighbor environment in GaInNAsSb alloys and homogenous alloy content (i.e., a homogenous QW profile after annealing). It is also worth noting that the narrower CER resonances are correlated with stronger QW emission. For both the first and second generations of GaInNAsSb laser structures, PL intensity from annealed samples was a few times stronger than the intensity from as-grown samples. In addition, PL intensity from the second generation of GaInNAsSb laser structures was stronger than the intensity from the first generation of GaInNAsSb structures. It means that CER spectroscopy is an independent method to verify the optimal annealing conditions.

In conclusion, the broadening of the fundamental transition in GaInNAsSb/GaNAs QWs, obtained at various growth and annealing conditions, was studied by CER spectroscopy. It has been shown that narrower CER resonances, therefore superior homogeneity of the QW profile, can be achieved by longer-duration and lower-temperature annealing. Such annealing conditions can be easily applied and controlled *in situ* during (and/or after) the growth of the upper part of laser structures. Also it has been concluded that the active part of a GaInNAsSb laser structure is rather far from an overannealing.

We acknowledge the support from the MNiSW Grant No. N515 074 31/3896 and the Foundation for Polish Science.

[1] M. Kondow, K. Uomi, A. Niwa, T. Kitatani, S. Watahiki, and Y. Yazawa, Jpn. J. Appl. Phys., Part 1 **35**, 1273 (1996).
[2] J. S. Harris, Jr., R. Kudrawiec, H. B. Yuen, S. R. Bank, H. P. Bae, M. A. Wistey, D. Jackrel, E. R. Pickett, T. Sarmiento, L. L. Goddard, V. Lordi, and T. Gugov, Phys. Status Solidi B **244**, 2707 (2007).
[3] S. R. Bank, H. P. Bae, L. L. Goddard, H. B. Yuen, M. A. Wistey, R. Kudrawiec, and J. S. Harris, Jr., IEEE J. Quantum Electron. **43**, 773 (2007), and references therein.
[4] J. A. Gupta, P. J. Barrios, X. Zhang, J. Lapointe, D. Poitras, G. Pakulski, X. Wu, and A. Delâge, Electron. Lett. **41**, 1060 (2005).
[5] T. Kageyama, T. Miyamoto, S. Makino, F. Koyama, and K. Iga, Jpn. J. Appl. Phys., Part 2 **38**, L298 (1999).
[6] V. Lordi, V. Gambin, S. Friedrich, T. Funk, T. Takizawa, K. Uno, and J. S. Harris, Phys. Rev. Lett. **90**, 145505 (2003).
[7] G. Mussler, L. Daeweritz, K. H. Ploog, J. W. Tomm, and V. Talalaev, Appl. Phys. Lett. **83**, 1343 (2003).
[8] E. M. Pavelescu, T. Jouhti, M. Dumitrescu, P. J. Klar, S. Karirinne, Y. Fedorenko, and M. Pessa, Appl. Phys. Lett. **83**, 1497 (2003).
[9] M. Kondow, T. Kitatani, and S. Shirakata, J. Phys.: Condens. Matter **16**, S3229 (2004).
[10] S. R. Bank, H. B. Yuen, H. Bae, M. A. Wistey, and J. S. Harris, Appl. Phys. Lett. **88**, 221115 (2006).
[11] H. P. Bae, S. R. Bank, H. B. Yuen, T. Sarmiento, E. R. Pickett, M. A. Wistey, and J. S. Harris, Appl. Phys. Lett. **90**, 231119 (2007).
[12] R. Kudrawiec, H. B. Yuen, K. Ryczko, J. Misiewicz, S. R. Bank, M. A. Wistey, H. P. Bae, and J. S. Harris, Jr., J. Appl. Phys. **97**, 053515 (2005).
[13] R. Kudrawiec, H. B. Yuen, M. Motyka, M. Gladysiewicz, J. Misiewicz, S. R. Bank, H. P. Bae, M. A. Wistey, and J. S. Harris, J. Appl. Phys. **101**, 013504 (2007).
[14] R. Kudrawiec, S. R. Bank, H. B. Yuen, M. A. Wistey, L. L. Goddard, J. S. Harris, M. Gladysiewicz, M. Motyka, and J. Misiewicz, Appl. Phys. Lett. **90**, 131905 (2007).
[15] M. Motyka, G. Sek, R. Kudrawiec, P. Sitarek, J. Misiewicz, J. Wojcik, B. J. Robinson, D. A. Thompson, and P. Mascher, J. Appl. Phys. **101**, 116107 (2007).
[16] M. Motyka, R. Kudrawiec, and J. Misiewicz, Phys. Status Solidi A **204**, 354 (2007).
[17] P. J. Klar, H. Grüning, J. Koch, S. Schäfer, K. Volz, W. Stolz, W. Heimbrodt, A. M. Kamal Saadi, A. Lindsay, and E. P. O'Reilly, Phys. Rev. B **64**, 121203 (2001).
[18] R. Kudrawiec, E.-M. Pavelescu, J. Andrzejewski, J. Misiewicz, A. Gheorghiu, T. Jouhti, and M. Pessa, J. Appl. Phys. **96**, 2909 (2004).
[19] R. Kudrawiec, E.-M. Pavelescu, J. Wagner, G. Sęk, J. Misiewicz, M. Dumitrescu, J. Konttinen, A. Gheorghiu, and M. Pessa, J. Appl. Phys. **96**, 2576 (2004).
[20] R. Kudrawiec, G. Sek, J. Misiewicz, D. Gollub, and A. Forchel, Appl. Phys. Lett. **83**, 2772 (2003).
[21] D. E. Aspnes, Surf. Sci. **37**, 418 (1973).