Materials Selection and Growth for Quantum Cascade Lasers and Detectors

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Abstract

Quantum cascade lasers (QCL) and detectors (QCD) enable spectroscopy in the MIR and THz finger print regions, spanning 3-300 µm [1, 2]. The properties of intersubband devices are determined by the material systems used and the band structure engineering they enable. The cubic III-V material systems have dominated due to the availability of high quality substrates (GaAs, InP, InAs, GaSb), lattice-matched or strain-compensated barriers, various conduction band offsets (CBO), low electron effective mass m_e^*, and available wave guiding.

We will present the growth of intersubband devices in different material systems by molecular beam epitaxy and the effects that this has on the device performance. Large CBOs and a high barrier effective mass m_e^* are helpful for creating short wavelength QCLs and QCDs. However, to improve long wavelength emission, up to the reststrahlen band and above it in the THz range, the large CBO and m_e^* leads to 1-2 monolayer (ML) thick barriers that are challenging to grow uniformly and reproducibly. InAs and $In_{0.53}Ga_{0.47}As$ are the lowest m_e^* well materials, so lattice-match III-AsSb have been developed to tune the CBO and m_e^*.

Symmetric THz QCLs have proven to be an excellent method to study material and interface quality, as well as dopant migration. Interface quality and asymmetry can be compared by the changes in the L-I-V curves for the two bias directions, figure 1. This allows the identification of higher quality normal InGaAs-to-InAlAs and inverted InAlAs-to-InGaAs interfaces [3]. For $InAs/AlAs_{0.16}Sb_{0.84}$ THz QCLs, the $AlAs_{0.16}Sb_{0.84}$ barriers are 1-2 ML and lead to more scattering [4], while 4 ML barriers are suitable for MIR QCDs [5].

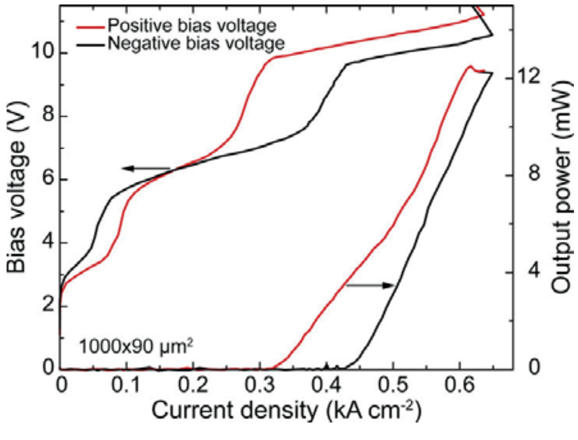

Fig. 1: Asymmetries in the InGaAs-to-InAlAs (normal) and InAlAs-to-InGaAs (inverted) interfaces lead to a measurable differences in the performance of symmetric THz QCLs.

In the quest to improve III-AsSb materials, like $GaAs_{1-x}Sb_x$ and $AlAs_ySb_{1-y}$, the As-for-Sb exchange becomes a significant factor in growth crystal quality, alloy composition, and latticematching [6, 7]. The III-As bonds are stronger than the III-Sb bonds, so that under a typical excess group V flux, the composition at the surface becomes group V ratio dependent, time, temperature, and growth rate dependent. The final stoichiometry and quality are the result of these variables. As shown in figure 2, $\mathrm{GaAs}_{1\text{-}x}\mathrm{Sb}_x$ was grown at the growth rates of 0.23 ML/s and 0.87 ML/s. Despite similar alloy compositions, the lower growth rate is partially relaxed and thus exhibits a much broader mosaic spread in the x-ray ω-scan, more dislocations and lower crystallinity.

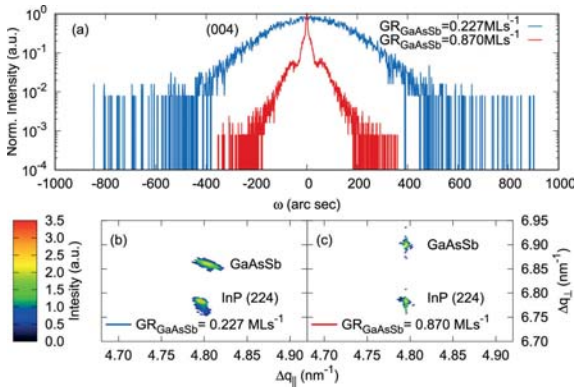

Fig. 2: (a) The mosaic spread (crystallinity) measured by high-resolution x-ray diffraction are greatly influenced by the growth rate of GaAsSb. Reciprocal space map of (b) 0.23 ML/s and (c) 0.87 ML/s.

We will present the growth and progress made in materials for MIR and THz devices, including which material system can be used reliably to reach 190 K pulse operations for THz QCLs.

References

[1] J. Faist, F. Capasso, D. L. Sivco, C. Sirtori, A. L. Hutchinson, and A. Y. Cho, “Quantum cascade laser,” Science **264**, 553–556 (1994).

[2] D. Hofstetter, M. Beck, and J. Faist, “Quantum-cascade-laser structures as photodetectors,” Applied Physics Letters **81**, 2683 (2002).

[3] C. Deutsch, M. A. Kainz, M. Krall, M. Brandstetter, D. Bachmann, S. Schönhuber, H. Detz, T. Zederbauer, D. MacFarland, A. M. Andrews, W. Schrenk, M. Beck, K. Ohtani, J. Faist, G. Strasser, and K. Unterrainer, “High power growth-robust InGaAs/InAlAs terahertz quantum cascade lasers,” ACS Photonics **4**, 957–962 (2017).

[4] M. Brandstetter, M. A. Kainz, T. Zederbauer, M. Krall, S. Schönhuber, H. Detz, W. Schrenk, A. M. Andrews, G. Strasser, and K. Unterrainer, “InAs based terahertz quantum cascade lasers,” Applied Physics Letters **108**, 011109 (2016).

[5] P. Reininger, T. Zederbauer, B. Schwarz, H. Detz, D. MacFarland, A. M. Andrews, W. Schrenk, and G. Strasser, “InAs/AlAsSb based quantum cascade detector,” Applied Physics Letters **107**, 081107 (2015).

[6] T. Zederbauer, A. M. Andrews, D. MacFarland, H. Detz, W. Schrenk, and G. Strasser, “Enhanced crystal quality of $\mathrm{Al}_x\mathrm{In}_{1-x}\mathrm{As}_y\mathrm{Sb}_{1-y}$ for terahertz quantum cascade lasers,” Photonics **3**, 20 (2016).

[7] T. Zederbauer, A. M. Andrews, D. MacFarland, H. Detz, W. Schrenk, and G. Strasser, “Incorporation of Sb and As in MBE grown GaAsxSb1-x layers,” APL Materials **5**, 035501 (2017).