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Extended density matrix model applied to tall barrier quantum cascade lasers

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Quantum cascade lasers (QCLs) are promising sources of terahertz (THz) radiation that have applications such as security and medical screening. While optical output power has recently exceeded 1 W [1], their highest operating temperature is currently limited to ~200 K [2] due to mechanisms such as thermal back filling and non-radiative phonon emission between lasing states. Another possible cause of performance degradation is parasitic leakage currents over barriers into continuum states as subband electron temperatures increase with lattice temperature. Novel designs with new injection schemes remain an intensive research area and new efforts are being made assuming that barrier heights no longer need to be constant [3,4]. A possible advantage of this is using tall barriers to reduce the leakage current, and in this work we present a theoretical study of recent experimental evidence [3] supporting this.

Interface roughness (IFR) scattering scales with the conduction band discontinuity squared and the calculations also assume a typical correlation length Λ and root mean roughness value Δ which are related to growth quality of the individual sample. We take typical values of Λ=60 Å and Δ=3 Å for these parameters. The QCL gain and current output characteristics are calculated using an extended density matrix solver which models transport through the injection barrier coherently. We obtain similar current and gain values (Figure 1) at resonance for both structures labeled 'NRC-V775A' and 'NRC-V775C' in ref. 3 indicating that the experimentally observed reduction in current density could be accredited to the reduction of parasitic current leakage.

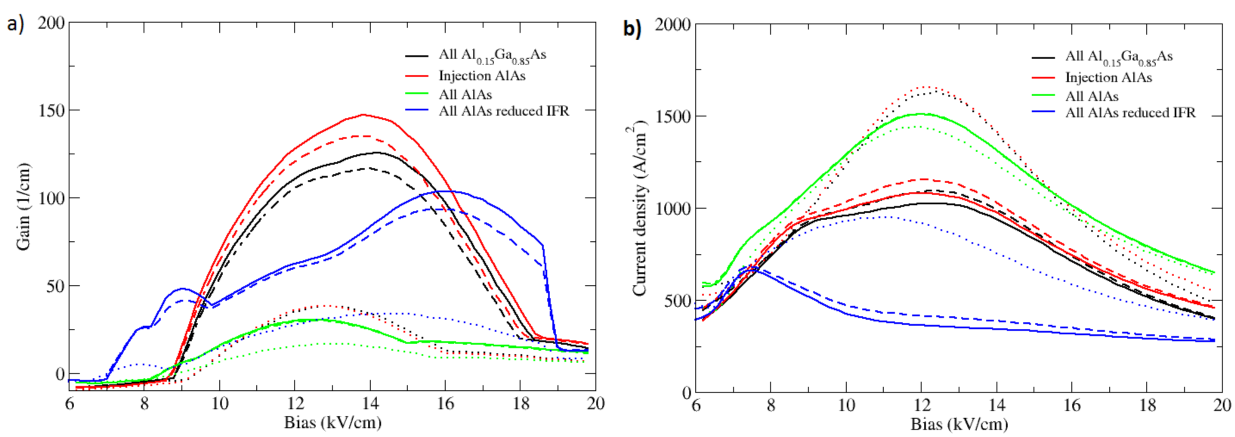

Figure 1: Gain (a) and current (b) versus applied bias for the reference structure [2], reference with AlAs injection barrier and all AlAs barrier structures [3] at 4.2 K (solid), 77 K (dashed) and 200 K (dotted) lattice temperatures.

Additionally, this work [3] attempted a similar design with all AlAs barriers which did not lase and it was conjectured that this was due to excessive IFR scattering as well as increased susceptibility to monolayer fluctuations with thinner layers. Our model, which accounts for the lifetime broadening in the gain calculation, confirms that modifying the IFR parameters to Λ=100 Å and Δ=1 Å (i.e. unrealistically sharp interfaces) leads to a significant improvement in performance as shown in Figure 1. We extend this work by proposing designs which aim to balance leakage current reduction and excessive scattering to achieve higher operating temperatures.

[1] L. Li et al., "Terahertz quantum cascade lasers with >1W output powers", Electronics Letters, 50, 4 (2014).
[2] S. Fathololoumi et al., "Terahertz quantum cascade lasers operating up to ~ 200 K with optimized oscillator strength and improved injection tunneling", Optics Express, 30, 003866 (2012).
[3] C. Wang et al., "Tall-barrier terahertz quantum cascade lasers", Applied Physics Letters, 103, 151117 (2013).
[4] A. Matyas et al., "Improved terahertz quantum cascade laser with variable height barriers", Journal of Applied Physics, 111, 103106 (2012).