THz intersubband electroluminescence from n-type Ge/SiGe quantum cascade structures

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We report electroluminescence originating from L-valley transitions in n-type Ge/Si0.12Ge0.88 quantum cascade structures centered at 3.4 and 4.9 THz with a line broadening of Δf/f ≈ 0.2. Three strain-compensated heterostructures, grown on a Si substrate by ultrahigh vacuum chemical vapor deposition, have been investigated. The design is based on a single quantum well active region employing a vertical optical transition and the observed spectral features are well described by non-equilibrium Green’s function calculations. The presence of two peaks highlights a suboptimal injection in the upper state of the radiative transition. Comparison of the electroluminescence spectra with similar GaAs/AlGaAs structure yields one order of magnitude lower emission efficiency.

Since the demonstration of the semiconductor diode laser and the high popularity of Si-based transistor technology, a laser on silicon constitutes a long-standing goal for silicon photonics.1 Significant advantages for a Si based laser should result from the high yield manufacturing processes to allow low cost at high volume but also enable low cost photonic systems from photonic integrated circuits. The major problem to realize a Si-based interband laser is the indirect band gap of group IV materials, which leads to a poor radiative recombination rate. Several solutions have been developed to achieve laser action from silicon.2–4 Employing intersubband transitions in quantum cascade structures represent an exciting option because such transitions are independent of the nature of the band gap.

So far the Quantum Cascade Laser (QCL)5 has only been demonstrated in polar III-V compound semiconductor materials based on transitions between conduction band states. Intersubband electroluminescence, however, due to valence band transitions from non-polar Si/SiGe heterostructures have been observed for mid-infrared6 and far-infrared wavelengths.7 The strained structure produces a complex valence band and the large effective mass (∼0.3m0)8,9 where m0 is the free electron mass) results in poor gain and therefore no subsequent laser action has been demonstrated. Theoretically n-type Ge/SiGe and Ge/GeSiSn material configurations with lower effective mass (∼0.135m0) are predicted to be promising candidates to realize a room temperature THz QCL9,10. Due to the absence of the restrahlen band, lasing transitions above 6 THz should be accessible. Because of the large lattice mismatch between Si and Ge, the growth of such Ge-rich structures on Si wafers is particularly challenging.11 Only in the last few years the Ge/SiGe heterostructures reached the quality standard required for this kind of application.12

While buried InGaAs/InAlAs QCLs13 operational in continuous wave and at room-temperature, de facto unlocked the mid-IR spectral region in different fields,14–15 THz QCLs remain limited to operation below room temperatures hindering potential applications. Pulsed Peltier-cooled operation of GaAs/AlGaAs THz QCLs was achieved in 201916 and recently demonstrated up to 250 K.17 The values of current density, high voltage drop per period and the temperature dependence of the subband lifetimes are intrinsically related to the polar nature of the gain material. Scattering of electrons with LO phonons ultimately limits the population inversion in such devices.

We recently proposed a Ge/SiGe quantum cascade design where non-equilibrium Green’s functions (NEGF) based calculations predict gain up to room temperature.18 The design is based on a 4-quantum well active region employing a bound-to-continuum transition and involves a total of four subband states. Although such a design approach holds good promise for the demonstration of a laser, it is not the ideal candidate to develop a new THz quantum cascade emitter. The diagonal optical transition leads to broad emission20 and a high voltage drop per period.

To unambiguously demonstrate electroluminescence from a Ge/SiGe quantum cascade structure, we adapted the GaAs/AlGaAs single quantum well (SQW) design reported in Ref.21. SQW active regions are not expected to show high optical gain. Instead, the low current density together with the moderate energy drop per period lead to reduced heating of the device. Hence, the unwanted blackbody emission can be reduced. The narrow spectral peak of the vertical intersubband transition should result in a clear signature in the spectrum. In this work, similar GaAs/AlGaAs structures with the same expected emission energy22 are used for a quantitative benchmark comparison with the Ge/SiGe results.

The conduction band profile in the L-valley and energy resolved current density of the target design is shown in Fig. 1(a). The main vertical transition between states 1 and
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FIG. 1. (a) Conduction band diagram and Wannier-Stark states for the target SQW design at 22 mV/period computed by NEGF. The solid black and solid grey lines are the potentials in the L- and Δ₅-valleys, respectively. The orange scale shows the position and energy resolved current density at 10 K. The integrated current density is 37 A/cm². The nominal period length is 82.4 nm with a sheet doping density of 2.54 × 10¹⁶ cm⁻². Starting from the injection barrier the nominal layer sequence with thicknesses in nanometers is 4₇/19.9/3.13/0.9/11.0/33.8/3.8/3/3/3/2/2/0.7. The Ge wells are in standard font, the Si₃.₅Ge₆.₅ barriers are in bold and the phosphorus doped layer is underlined. (b) Reciprocal space map acquired on sample 2306 around asymmetric (4 ¯2¯2) Si reflections. (c) Comparison of the measured and simulated (004) XRD rocking curve. The simulated curve is shifted for clarity. (d) STEM image at different magnifications of the growth direction is reversed the polarity is switched. If a SQW heterostructure. The SiGe barriers appear darker. (e) SEM image and schematic diagram of the Ge/SiGe interdigitated diffraction grating. The schematic diagram shows the cross-section of a single grating finger and its bias configuration for the regular growth direction. If the growth direction is reversed the polarity is switched.

The active region consists of 51 periods of the SQW region design (see Fig. 1(a)) for a total thickness of 4.2 μm. The main sample parameters including the GaAs/AlGaAs reference discussed in this work are listed in Table I. The (422) x-ray diffraction (XRD) reciprocal space map of sample 2306 depicted in Fig. 1(b) shows the lattice matching of the active region to the Si₃.₅Ge₆.₅ buffer as evidenced by the alignment of the superlattice peaks with the Si₃.₅Ge₆.₅ signal along the vertical dotted line. The active region period length L₀ and its reproducibility is derived from 1D XRD rocking curves, see Fig. 1(c). The scanning transmission electron mic-

Table I. Overview of the quantum cascade structures: Sample ID, nominal sheet doping density n₂D, period length L₀ measured by XRD and the number of periods N₀.

| Sample ID | n₂D (10¹⁶cm⁻²) | L₀ (nm) | N₀ |
|-----------|----------------|---------|----|
| 2306      | 5              | 85.4    | 51 |
| 2307      | 7              | 83.3    | 51 |
| 2315⁵      | 7              | 87.8    | 51 |
| S1353⁴      | 2.9            | 97.7    | 35 |

⁴ reverse growth direction
⁵ reference GaAs/Al₀.₁₅Ga₀.₈₅As sample
The voltage-current (VI) and electroluminescence measurements were performed in a home-made, vacuum Fourier transform infrared (FTIR) spectrometer equipped with a He-cooled Si bolometer (IR Labs). The samples were mounted in a He flow cryostat. The heat sink temperature was kept at 5 K. The setup was pre-aligned and phase calibrated using a vertically emitting single mode THz QCL and phase calibrated using a vertically emitting single mode THz QCL equipped with a He-cooled Si bolometer (IR Labs). The samples were mounted in a He flow cryostat. The heat sink temperature was kept at 5 K. The setup was pre-aligned and phase calibrated using a vertically emitting single mode THz QCL and phase calibrated using a vertically emitting single mode THz QCL driven below threshold. Current was injected following a micro-macro pulse scheme to minimize heating effects. Generally, 627 micro-pulses of 960 ns length (equivalent to a duty-cycle of $D = 50\%$) with macro-pulse frequency of 415 Hz are used. The interferograms were acquired in step-scan mode with a lock-in amplifier with 2 s integration time per point and a spectral resolution of $\Delta \nu = 0.82$ meV (198 GHz). Multiple interferograms with the same experimental conditions were averaged yielding typically 8-24 hours of total integration time. The stabilities of the in-phase component, quadrature component and the heat sink temperature were verified continuously during the acquisition time.

The voltage-current (VI) and electroluminescence intensity-current (LI) characteristics measured at 5 K for the Ge/SiGe samples and the GaAs/AlGaAs reference sample are visible in Fig. 2. (VI curves as a function of the temperature up to 290 K are reported in the Supplementary Material). The observed Ge/SiGe VI curves are compared to the NEGF simulation for sample 2307; the measured current density exceeds the simulated one by a factor of 5, that is consistent with theoretical lifetimes predictions, as discussed further below. Comparing the VI curves of the Ge/SiGe samples to the GaAs reference measurement, the current density for the same applied electric field is one order of magnitude larger. Additionally, the transport of the Ge/SiGe samples does not show signs of negative differential resistance (NDR) as clearly observed in the reference sample at a current density of 42 A/cm$^2$. From Fig. 2(a), it can be seen that the spectra of the Ge/SiGe samples are acquired at low injection currents (< 200 mA or 1.8 kA/cm$^2$) to prevent any blackbody emission overwhelming the intersubband signal.

Typical spectra measured on the three Ge/SiGe samples are shown in Fig. 3(a)-(c). Two peaks centered around 13 meV and 22 meV appear distinctly from the spectra. We identify the first peak as the vertical transition between states $|2\rangle$ and $|1\rangle$, see Fig. 1(a). We attribute the second peak to a transition from a higher lying energy state $|p\rangle$ to the upper state of the miniband $|u\rangle$, which extracts the electrons from the SQW. In Fig. 3(c) we report as well the predicted electroluminescence spectra using NEGF. Two peaks are predicted, in fair agreement with the measurements: the presence of the second peak highlights the role of hot electrons due to the absence of strong inelastic scattering (LO phonons). The measured spectra are
fitted to a double Lorentzian function and the extracted transition energies are compared to the simulated peak positions as a function of the period length, see Fig. 3(d). The measurement and simulations agree to within 2 meV. Note that in simulations we account for the different period lengths obtained by XRD and the nominal doping density is used (see Table I). The small discrepancy of the peak positions may be due to some uncertainty related to the material parameters of the Ge/SiGe system (band-offset and electron effective mass), as well as to the exact knowledge of the actual doping profile. In Fig. 3(e) the extracted FWHM and the integrated peak power of the individual transitions are shown. The observed FWHMs agree with optical absorption measurements reported in Refs. 30,39. Considering sample 2306 the line broadening for both peaks is $\Delta f/f \approx 0.2$. The FWHM of the $\langle 2 \rangle$ to $\langle 1 \rangle$ transition is 2.5 meV, which is 1 meV larger than what is predicted by NEGF. In the context of the Kazarinov-Suris density matrix model for transport in quantum cascade structures,20,21 this linewidth corresponds to a dephasing lifetime $T_2 \approx 0.3$ ps. It has to be mentioned that a control sample with the doping placed homogeneously over four quantum wells of the injector and processed in identical gratings has given, as expected, a low intensity, broad signal with no significant spectral features. Such measurements and additional reverse bias measurements are reported in the Supplementary Material.

The spectrum of the GaAs/AlGaAs reference sample is reported in Fig. 3(f). It is acquired at the maximum current value before the NDR. The peak is centered at 14.8 meV with a FWHM of 0.7 meV ($\Delta f/f \approx 0.05$) and integrated peak power of 2.5 pW. Only one peak appears due to proper electronic injection into the upper state $\langle 2 \rangle$ and an accurate doping level. However, above the NDR two peaks have been reported due to broad injection into high-energy states,26 where the corresponding spectrum resembles the spectra of the Ge/SiGe samples. The smaller confinement offset in our Si$_{0.15}$Ge$_{0.85}$ design energetically lower the parasitic state $\langle p \rangle$. The weaker electron-phonon interaction in non-polar Ge/SiGe active region leads to a larger electronic excess temperature.23,42 Thus, the transport through higher lying energy states is non negligible and leads to a second optically active transition. Additionally, the doping level in the active region and the contacts of our structures are not optimized. This could cause a non-homogeneous electric field across the 51 periods of the cascade and ultimately impair the electronic injection.
In the following the non-radiative lifetimes of the upper states $|2\rangle$ and $|p\rangle$ are estimated, considering the spectrum of sample 2315 and using the GaAs reference to extract the collection efficiency. The electroluminescence power can be written as

$$P_{\text{opt}} = \eta_{\text{inj}} \eta_{\text{coll}} \frac{h\nu}{e} N_D \tau \cdot I,$$

where $\eta_{\text{coll}}$ is the collection efficiency for the setup and the grating, $\eta_{\text{rad}} \approx \tau_{\text{nr}}/\tau_{\text{p}}$ the radiative efficiency, $h\nu$ the photon energy, $\tau$ the duty-cycle, $I$ the current and $e$ the absolute charge of an electron. In the case of GaAs, we assume unitary current injection $\eta_{\text{inj}} = 1$ (NDR well visible), we use $\tau_{\text{nr}} = 12.2\text{ ps}$, and, with the computed spontaneous emission lifetime $\tau_{\text{sp}} = 7.4\text{ ps}$ we can extract a collection efficiency of $\eta_{\text{coll}} \approx 7 \times 10^{-4}$. For the Ge/SiGe structure we assume that the total power is given by sum of the two peaks (see supplementary material). The injection efficiencies into states $|2\rangle$ and $|p\rangle$ computed with NEGF simulations are $\eta_{\text{inj},2} = 0.38$ and $\eta_{\text{inj},p} = 0.37$. Using the computed spontaneous emission lifetimes $\tau_{\text{sp},2} = 15.9\text{ ps}$ and $\tau_{\text{sp},p} = 7.1\text{ ps}$, we obtain $\tau_{\text{nr},2} = 1.9\text{ ps}$ and $\tau_{\text{nr},p} = 1.3\text{ ps}$. Consequently, the radiative efficiency is $\eta_{\text{rad}} \approx 10^{-2}$. The lifetimes predicted by NEGF modelling are $\tau_{\text{sim},2} = 12\text{ ps}$ and $\tau_{\text{sim},p} = 6\text{ ps}$, roughly a factor of 5 higher. We stress that the deduced values for the lifetimes constitute a lower limit; the actual injection efficiency is not higher electronic temperature. In fact, NEGF simulations suggest that Coulomb scattering prevails over interface roughness in the determination of the lifetimes and of the linewidth.

In conclusion, THz intersubband electroluminescence from n-type Ge/Si$_{0.15}$Ge$_{0.85}$ quantum cascade structures has been demonstrated from three different epitaxial layers. The spectral features agree well with theoretical predictions based on the non-equilibrium Green’s function simulations. The emitters have been benchmarked against a similar GaAs/AlGaAs structure with identical device geometry. The Ge/SiGe emission efficiency is one order of magnitude lower. This is attributed to a suboptimal injection of the electrons into the upper state of the radiative transitions and to a lower upper state lifetime. Future improvements will come from a more accurate control of the doping profile, a better understanding of its interaction with the threading dislocations and from a further reduction of their density. Finally it would be useful to clarify whether the $\Delta_2$-states confined in the barriers influence the electronics dynamics. To achieve laser action, we will leverage on the progress made in the material growth and structure modelling by employing higher gain structures based on 4-quantum well and featuring a diagonal optical transition and embedded in double metal waveguide.

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1. D. Liang and J. E. Bowers, “Recent progress in lasers on silicon,” Nature Photonics 4, 511–517 (2010).
2. G. Boyraz and B. Jalali, “Demonstration of a silicon Raman laser,” Optics Express 12, 5259–5273 (2004).
3. T. Armand Plon, A. Lysaot, Y.-M. Niquet, V. Reboud, V. Calvo, N. Pauw, J. Widiez, C. Bonzon, J. M. Hartmann, A. Chelnokov, J. Faist, and H. Sigg, “Lasing in strained germanium microbridges,” Nature Communications 10, 2724 (2019).
4. Y. Wan, S. Zhang, J. C. Norman, M. J. Kennedy, W. He, S. Liu, C. Xiang, C. Shang, J.-J. He, A. C. Gossard, and J. E. Bowers, “Tunable quantum dot lasers grown directly on silicon,” Optica 6, 1394 (2019).
5. M. Seifried, G. Villares, Y. Baumgartner, H. Hahn, M. Halter, F. Horst, D. Caimi, C. Caër, M. Sousa, R. F. Dang, L. Czornomaz, and B. Jalali, “Monolithically Integrated CMOS-Compatible III–V on Silicon Lasers,” IEEE Journal of Selected Topics in Quantum Electronics 24, 1–9 (2018).
6. H. Nguyen-Van, A. N. Baranov, Z. Loghmari, L. Cerutti, J.-B. Rodriguez, J. Tournet, G. Nary, G. Boissier, G. Patriarche, M. Bahriz, E. Tournié, and R. Teissier, “Quantum cascade lasers grown on silicon,” Scientific Reports 8, 7206 (2018).
7. J. Faist, F. Casp, D. L. Sicco, C. Sirtori, A. L. Hutchinson, and A. Y. Cho, “Quantum Cascade Laser,” Science, 264, 553–556 (1994).
8. G. Dehlinger, L. Drehi, U. Gennser, H. Sigg, J. Faist, K. Ensslin, D. Grützmacher, and E. Müller, “Intersubband Electroluminescence from Silicon-Based Quantum Cascade Structures,” Science 290, 2277–2280 (2000).
9. A. A. Lynch, R. Bates, D. J. Paul, D. J. Norris, A. G. Cullis, Z. Ikonic, R. W. Kellsal, P. Harrison, D. D. Aronne, and C. R. Pidgeon, “Intersubband electroluminescence from Si/SiGe cascade emitters at terahertz frequencies,” Applied Physics Letters 81, 1543–1545 (2002).
10. D. J. Paul, “The progress towards terahertz quantum cascade lasers on silicon substrates,” Laser & Photonics Reviews 4, 610–632 (2010).
11. G. Matton, D. J. Paul, L. Lever, M. Califano, Z. Ikonic, R. W. Kellsal, J. Zhang, D. Christana, G. Isella, H. von Kanel, E. Müller, and A. Neels, “Si/SiGe quantum cascade superlattice designs for terahertz emission,” Journal of Applied Physics 107, 053110 (2010).
12. K. Driscoll and R. Paella, “Silicon-based injection lasers using electronic intersubband transitions in the L valleys,” Applied Physics Letters 89, 191110 (2006).
13. K. Driscoll and R. Paella, “Design of n-type silicon-based quantum cascade lasers for terahertz light emission,” Journal of Applied Physics 102, 093103 (2007).
14. G. Sun, H. H. Cheng, J. Menéndez, J. B. Khurgin, and R. A. Soref, “Strain-free Ge/GeSn quantum cascade lasers based on L-valley intersubband transitions,” Applied Physics Letters 90, 251105 (2007).
15. A. Valavanis, T. V. Dinh, L. J. M. Lever, Z. Ikonic, and R. W. Kellsal, “Material configurations for n-type silicon-based terahertz quantum cascade lasers,” Physical Review B 83, 195321 (2011).
16. G. Grange, S. Mukherjee, G. Capellini, M. Mostanari, L. Persichetti, L. Di Gaspare, S. Birner, A. Attiaou, O. Moutanabib, M. Virgilio, and M. De Setta, “Atomic-Scale Insights into Semiconductor Heterostructures: From Experimental Three-Dimensional Analysis of the Interface to a Generalized Theory of Interfacial Roughness Scattering,” Physical Review Applied 13, 044062 (2020).
17. M. Beck, “Continuous Wave Operation of a Mid-Infrared Semiconductor Laser at Room Temperature,” Science 295, 301–305 (2002).
18. M. S. Vitiello, G. Scalari, B. Williams, and P. D. Natale, “Quantum cascade lasers: 20 years of challenges,” Optics Express 23, 5167–5182 (2015).
19. F. Galli, S. Bartalini, S. Borti, P. Caneo, D. Mazzotti, F. De Natale, and G. Giusfredi, “Molecular Gas Sensing Below Parts Per Trillion: Radiocarbon-Dioxide Optical Detection,” Physical Review Letters 107, 270802 (2011).
20. J. L. Klocke, M. Mangold, P. Allmendinger, A. Hugi, M. Geiser, P. Jouy, J. Faist, and T. Kottke, “Single-Shot Sub-microsecond Mid-infrared Spec-
THz intersubband electroluminescence from n-type Ge/SiGe quantum cascade structures

24. T. Grange, D. Stark, G. Scalari, J. Faist, L. Persichetti, L. Di Gaspare, M. De Seta, M. Ortolani, D. J. Paul, G. Capellini, S. Birner, and M. Virgilio, “Room temperature operation of n-type Ge/SiGe terahertz quantum cascade lasers predicted by non-equilibrium Green’s functions,” Applied Physics Letters 114, 111102 (2019).

25. S. Blaser, M. Rochat, M. Beck, J. Faist, and U. Oesterle, “Far-infrared emission and Stark-cyclotron resonances in a quantum-cascade structure based on photon-assisted tunneling transition,” Physical Review B 61, 8369–8374 (2000).

26. G. Scalari, R. Terazzi, M. Giovannini, N. Hoyler, and J. Faist, “Population inversion by resonant tunneling in quantum wells,” Applied Physics Letters 91, 032103 (2007).

27. M. Rochat, J. Faist, M. Beck, U. Oesterle, and M. Ilegems, “Far-infrared (λ=88µm) electroluminescence in a quantum cascade structure,” Applied Physics Letters 73, 3724–3726 (1998).

28. T. Grange, “Electron transport in quantum wire superlattices,” Physical Review B 89, 165310 (2014).

29. G. Scalari, R. Terazzi, M. Giovannini, N. Hoyler, and J. Faist, “Population inversion by resonant tunneling in quantum wells,” Applied Physics Letters 91, 032103 (2007).

30. M. Rochat, J. Faist, M. Beck, U. Oesterle, and M. Ilegems, “Far-infrared (λ=88µm) electroluminescence in a quantum cascade structure,” Applied Physics Letters 73, 3724–3726 (1998).

31. T. Grange, “Electron transport in quantum wire superlattices,” Physical Review B 89, 165310 (2014).

32. G. Scalari, R. Terazzi, M. Giovannini, N. Hoyler, and J. Faist, “Population inversion by resonant tunneling in quantum wells,” Applied Physics Letters 91, 032103 (2007).

33. M. Rochat, J. Faist, M. Beck, U. Oesterle, and M. Ilegems, “Far-infrared (λ=88µm) electroluminescence in a quantum cascade structure,” Applied Physics Letters 73, 3724–3726 (1998).

34. T. Grange, “Electron transport in quantum wire superlattices,” Physical Review B 89, 165310 (2014).

35. G. Scalari, R. Terazzi, M. Giovannini, N. Hoyler, and J. Faist, “Population inversion by resonant tunneling in quantum wells,” Applied Physics Letters 91, 032103 (2007).

36. M. Rochat, J. Faist, M. Beck, U. Oesterle, and M. Ilegems, “Far-infrared (λ=88µm) electroluminescence in a quantum cascade structure,” Applied Physics Letters 73, 3724–3726 (1998).

37. T. Grange, “Electron transport in quantum wire superlattices,” Physical Review B 89, 165310 (2014).

38. G. Scalari, R. Terazzi, M. Giovannini, N. Hoyler, and J. Faist, “Population inversion by resonant tunneling in quantum wells,” Applied Physics Letters 91, 032103 (2007).

39. M. Rochat, J. Faist, M. Beck, U. Oesterle, and M. Ilegems, “Far-infrared (λ=88µm) electroluminescence in a quantum cascade structure,” Applied Physics Letters 73, 3724–3726 (1998).

40. T. Grange, “Electron transport in quantum wire superlattices,” Physical Review B 89, 165310 (2014).

41. G. Scalari, R. Terazzi, M. Giovannini, N. Hoyler, and J. Faist, “Population inversion by resonant tunneling in quantum wells,” Applied Physics Letters 91, 032103 (2007).

42. M. Rochat, J. Faist, M. Beck, U. Oesterle, and M. Ilegems, “Far-infrared (λ=88µm) electroluminescence in a quantum cascade structure,” Applied Physics Letters 73, 3724–3726 (1998).

43. T. Grange, “Electron transport in quantum wire superlattices,” Physical Review B 89, 165310 (2014).

44. G. Scalari, R. Terazzi, M. Giovannini, N. Hoyler, and J. Faist, “Population inversion by resonant tunneling in quantum wells,” Applied Physics Letters 91, 032103 (2007).

45. M. Rochat, J. Faist, M. Beck, U. Oesterle, and M. Ilegems, “Far-infrared (λ=88µm) electroluminescence in a quantum cascade structure,” Applied Physics Letters 73, 3724–3726 (1998).

46. T. Grange, “Electron transport in quantum wire superlattices,” Physical Review B 89, 165310 (2014).

47. G. Scalari, R. Terazzi, M. Giovannini, N. Hoyler, and J. Faist, “Population inversion by resonant tunneling in quantum wells,” Applied Physics Letters 91, 032103 (2007).

48. M. Rochat, J. Faist, M. Beck, U. Oesterle, and M. Ilegems, “Far-infrared (λ=88µm) electroluminescence in a quantum cascade structure,” Applied Physics Letters 73, 3724–3726 (1998).

49. T. Grange, “Electron transport in quantum wire superlattices,” Physical Review B 89, 165310 (2014).

50. G. Scalari, R. Terazzi, M. Giovannini, N. Hoyler, and J. Faist, “Population inversion by resonant tunneling in quantum wells,” Applied Physics Letters 91, 032103 (2007).

51. M. Rochat, J. Faist, M. Beck, U. Oesterle, and M. Ilegems, “Far-infrared (λ=88µm) electroluminescence in a quantum cascade structure,” Applied Physics Letters 73, 3724–3726 (1998).

52. T. Grange, “Electron transport in quantum wire superlattices,” Physical Review B 89, 165310 (2014).

53. G. Scalari, R. Terazzi, M. Giovannini, N. Hoyler, and J. Faist, “Population inversion by resonant tunneling in quantum wells,” Applied Physics Letters 91, 032103 (2007).

54. M. Rochat, J. Faist, M. Beck, U. Oesterle, and M. Ilegems, “Far-infrared (λ=88µm) electroluminescence in a quantum cascade structure,” Applied Physics Letters 73, 3724–3726 (1998).

55. T. Grange, “Electron transport in quantum wire superlattices,” Physical Review B 89, 165310 (2014).

56. G. Scalari, R. Terazzi, M. Giovannini, N. Hoyler, and J. Faist, “Population inversion by resonant tunneling in quantum wells,” Applied Physics Letters 91, 032103 (2007).

57. M. Rochat, J. Faist, M. Beck, U. Oesterle, and M. Ilegems, “Far-infrared (λ=88µm) electroluminescence in a quantum cascade structure,” Applied Physics Letters 73, 3724–3726 (1998).

58. T. Grange, “Electron transport in quantum wire superlattices,” Physical Review B 89, 165310 (2014).

59. G. Scalari, R. Terazzi, M. Giovannini, N. Hoyler, and J. Faist, “Population inversion by resonant tunneling in quantum wells,” Applied Physics Letters 91, 032103 (2007).

60. M. Rochat, J. Faist, M. Beck, U. Oesterle, and M. Ilegems, “Far-infrared (λ=88µm) electroluminescence in a quantum cascade structure,” Applied Physics Letters 73, 3724–3726 (1998).

61. T. Grange, “Electron transport in quantum wire superlattices,” Physical Review B 89, 165310 (2014).