Optical gain of two-dimensional hole gas by intersubband Raman transitions

Soichiro Tsujino^{a)}

Laboratory for Micro- and Nanotechnology, Paul Scherrer Institut, CH-5232 Villigen-PSI, Switzerland

(Received 18 February 2012; accepted 20 June 2012; published online 19 July 2012)

Raman gain of a two-dimensional hole gas is theoretically studied. It is shown that a finite gain is expected for a *p*-type quantum well without introducing asymmetry via a Raman transition between confined hole states. The gain and loss in SiGe and Ge quantum wells on Si substrates by hole intersubband transitions are modeled using an experimentally validated 6-band *k*·*p* method combined with a design of a SiGe ridge waveguide on Si substrate. A net modal gain of $\sim 20 \text{ cm}^{-1}$ with the pump intensity of $\sim 4 \text{ MW cm}^{-2}$ is predicted for a device with multiple square Ge quantum well active layers by the proposed intersubband Raman transition. © 2012 American Institute of Physics. [<http://dx.doi.org/10.1063/1.4737575>]

I. INTRODUCTION

Optical components using Si-based materials have been intensely studied to surmount the potential bottleneck of the electrical interconnects in short and medium distances between microprocessor chips.¹ Si-based photonic devices such as Si Raman laser,² Ge laser,³ and modulator⁴ utilizing the interband transitions in Ge prepared on Si,^{5,6} and defects^{7,8} or quantum-dot-embedded⁹ Si light emitting diodes have been reported recently. A different approach utilizes optical transitions between confined states in high Ge-content SiGe and Ge quantum wells with large valence band energy offsets. In contrast to the interband transitions between conduction band and valence band, transition energies of the inter-subband transitions can be largely tailored by design.^{10–17} Electroluminescence from strain-compensated Si-SiGe quantum cascade structure was reported, but lasing has remained to be a challenge because of the insufficient optical gain with respect to the waveguide loss, in particular from current injector layers.¹⁴

In this work, optical gain of a two-dimensional hole gas in strain-compensated SiGe quantum wells generated by optical pumping is explored. In contrast to the electrically pumped structures, the absence of current injectors and associated waveguide loss is likely to offer a critical advantage to achieve lasing. Moreover, optical pumping scheme allows one to study basic optical transitions in simpler device structures. Here, a Raman transition in a three-level system formed in high-Ge content *p*-type SiGe wells is considered. Unlike *n*-type quantum wells studied in the past,^{18–22} large Raman gain is predicted in a square quantum well without introducing asymmetry by combining a TM-polarized transition between light-hole (LH) states with a TE-polarized transition between LH and heavy-hole (HH) state. In SiGe systems, because of the large HH effective mass and the large intersubband linewidth broadening by the interface-roughness scattering,¹⁵ the proposed Raman gain in square wells is more robust and advantageous than in asymmetric wells utilizing solely TM-polarized HH-transitions.

II. INTERSUBBAND RAMAN GAIN IN *p*-TYPE SQUARE SiGe QUANTUM WELLS

The intersubband Raman gain spectrum for a *signal* photon (S) with energy E_s excited by a *pump* photon (P) with energy E_p is given by the following equation when E_s is close to the transition energy E_{32} between the third level (3) and the second level (2) and E_p is close to the transition energy E_{13} between the ground level (1) and 3 at the same time,

$$G_R(E_s, E_p) = \frac{4\pi\alpha}{\eta_s} \omega_s z_{32}^2 \text{Re} \left[\frac{|e_p|^2}{\Gamma_{32}\Gamma_{13}\Gamma_{12}} \frac{(p_1 - p_3)}{1 + |e_p|^2/(\Gamma_{32}\Gamma_{12})} \right]. \quad (1)$$

In Eq. (1), α is the fine structure constant, η_s is the refractive index, p_n are hole concentrations in the *n*-th level, and z_{32} is the dipole moment of the transition between 3 and 2. The pump excitation is introduced as the Rabi frequency e_p given by $e_0 r_{13} F_p / (2\hbar)$ with the elementary charge e_0 , the dipole moment r_{13} of the 1-to-3 transition, and the electric field F_p of the pump. In Eq. (1), following detunings were defined, $\Gamma_{13} = \gamma_{13} - i\Delta$, $\Delta = (E_{31} - E_p)/\hbar$, $\Gamma_{23} = \gamma_{23} - i\delta$, $\delta = (E_{32} - E_s)/\hbar$, and $\Gamma_{12} = \gamma_{12} - i(\Delta - \delta)$, with γ_{nm} the dephasing rate of the *n*-to-*m* optical transition. Equation (1) is obtained from a steady state solution of the density-matrix within the rotating-wave approximation, solved together with the Maxwell's equation with the envelope-function approximation.¹⁸

In a *p*-type square quantum well, one can identify the first heavy hole level H1 as 1, the first light hole level L1 as 2, and the second light hole level L2 as 3, see Figs. 1(a) and 2(a). In *n*-type quantum wells, spatial asymmetry is crucial to form a three-level system with finite r_{13} , but not in valence band. Whereas the *S*-transition with the matrix element z_{32} is TM active (polarization perpendicular to the quantum well plane), the *P*-transition with the matrix element r_{13} is TE active because of the interband nature of the HH to LH transition. The largest optical loss originates from the TM active absorption transition from H1 to the second heavy hole level H2, since the energy difference δE between the H1-to-H2 transition energy E_{H1-H2} and E_3 (the L2-to-L1 transition

^{a)}Electronic mail: soichiro.tsujino@psi.ch.

FIG. 1. (a) Hole energy levels of QW1 at $k=0$ for a $\text{Si}_{0.2}\text{Ge}_{0.8}$ quantum well (5 nm) separated by 3 nm-thick Si barriers. $\text{Si}_{0.5}\text{Ge}_{0.5}$ substrate is assumed. (b) Net optical gain as a function of the pump photon energy and signal photon energy with the pump intensity of 11.9 MW cm^{-2} calculated by 6-band $k\cdot p$ method. (c) Absorption and gain when pump photon energy is 0.2388 eV with the same pump intensity assumed in (b).

energy) is small. In the case of strain-compensated SiGe quantum wells, δE is in the order of tens of meV for nearly all the range of Ge content. However, the non-zero δE makes the net gain finite at sufficiently high pump excitation intensity. In the simulation shown below, it is shown that the required pump excitation intensity to reach transparency and lasing is moderate.

The quantum well in Figure 1(a), QW1, is a square $\text{Si}_{0.2}\text{Ge}_{0.8}$ well with Si barriers strain-compensated to a $\text{Si}_{0.5}\text{Ge}_{0.5}$ pseudo substrate, a material combination of which growth and optical transitions were studied in Refs. 13–15, 21, and 22. Fig. 1(a) depicts the energy levels at the Γ -point where the in-plane wave vector $k=0$, calculated by a 6-band

$k\cdot p$ method. The band-offsets, deformation potentials, and Luttinger parameters used in the calculation were validated previously by comparisons with experiments such as the valence band intersubband absorption spectra including the LH-HH mixing,^{16,17} high-peak-to-value ratio hole resonant tunneling in SiGe/Ge double-barrier diode,²³ and direct-gap interband optical transition spectra in Ge quantum wells.⁶ Hole concentration per quantum well equal to $0.5 \times 10^{12} \text{ cm}^{-2}$ was assumed. The gain and loss are obtained by integrating those for each k -state within $|k|$ below the Fermi wave vector k_F .

To estimate the dephasing rates γ_{nm} , experimental absorption spectra of $\text{Si}_{0.2}\text{Ge}_{0.8}$ quantum wells on $\text{Si}_{0.5}\text{Ge}_{0.5}$

FIG. 2. (a) Hole energy levels of QW2 at $k=0$ for a Ge quantum well (5 nm) separated by $\text{Si}_{0.8}\text{Ge}_{0.2}$ barriers (3 nm). $\text{Si}_{0.3}\text{Ge}_{0.7}$ substrate is assumed. (b) Net optical gain as a function of the pump photon energy and signal photon energy with the pump intensity of 4.19 MW cm^{-2} calculated by 6-band $k\cdot p$ method. (c) Absorption and gain coefficient when pump photon energy is 0.2798 eV with the same pump intensity assumed in (b).

pseudo-substrates in Ref. 17 with the hole concentration of $1 \times 10^{12} \text{ cm}^{-2}$ were consulted. The observed linewidth broadening (half width at the half maximum) of the H1-H2 transitions in 4.5 nm-thick and 5.5 nm-thick wells were 21 meV and 12 meV, respectively. The linewidth broadening of the H1-L2 transitions was 16 meV for 4.5 nm-thick well, and 11 meV for 5.5 nm well, respectively, whereas the linewidth of H1-L1 transitions was approximately same as H1-H2. Comparing these values with the linewidth of calculated absorption spectra for the same hole concentration, it was found that the k -dispersion of the transition energy increased linewidth of the H1-H2 transition by (1-2) meV for both wells, and the linewidth of the H1-L2 transition by 6 meV and 11 meV for 5.5 nm- and 4.5 nm-thick wells, respectively. Therefore, $\gamma_{\text{H1-H2}}$, $\gamma_{\text{H1-L2}}$, and $\gamma_{\text{H1-L1}}$ were assumed to be 10 meV. There were no direct absorption data for the L1-L2 transition, so $\gamma_{\text{L1-L2}}$ was approximated by $(\gamma_{\text{H1-L1}} + \gamma_{\text{H1-L2}})/2$.

Transient population in excited levels under optical pumping can modify the gain and loss. It can also cause the re-absorption of the S -photon. However, unlike III-V semiconductor case, it is not important in SiGe wells for excitation intensity of $2\text{--}20 \text{ MW cm}^{-2}$ considered in the following. Therefore this effect was neglected. In fact, the optical excitation rate, which is below $2|e_p|^2/\gamma_{31}$ and at most 0.4 ps^{-1} for 20 MW cm^{-2} with γ_{31} of 10 meV and r_{13} of 0.39 nm, is an order of magnitude smaller than expected L2-level relaxation lifetime of $7\text{--}10 \text{ ps}^{-1}$ (Refs. 24 and 25).

III. GAIN AND LOSS IN STRAIN-COMPENSATED SiGe-Si AND Ge-SiGe WELLS

Figure 1(b) shows the spectrum of the net gain, G_R subtracted by the H1-H2 absorption, calculated for QW1 for TE-polarized *pump* with E_p near 0.24 eV and TM-polarized *signal* with E_s around 0.16 eV, when the well is excited with the pump intensity I_p of 11.9 MW cm^{-2} . Fig. 1(c) shows G_R and the H1-H2 absorption separately as a function of E_s at the same I_p with E_p of 0.239 eV. A finite net gain of 30 cm^{-1} is obtained at E_s of 0.1573 eV with this excitation condition, despite the large absorption by the H1-H2 transition centered at $\sim 0.13 \text{ eV}$, because of the finite detuning of the L2-L1 transition from the H1-H2. This E_s is more than 10 meV larger than $E_{\text{L2-L1}}$, since the loss by the H1-H2 transition absorption decreases rapidly at higher energy.

Increasing the energy separation δE between $E_{\text{H1-H2}}$ and $E_{\text{L2-L1}}$ without degrading the Raman transition matrix elements is a key to lower the pump intensity. While designs including coupled quantum wells or asymmetric wells are common in III-V structures, their effectiveness is limited for SiGe structures due to the interface-roughness-induced linewidth broadening of the transitions.¹⁵ As an alternative strategy, square wells with different Ge contents were considered, which lead to the finding that QW2 shown in Fig. 2(a), a 5 nm-thick square Ge well with $\text{Si}_{0.8}\text{Ge}_{0.2}$ barriers on a $\text{Si}_{0.3}\text{Ge}_{0.7}$ substrate, exhibits δE of $\sim 50 \text{ meV}$. Both of the matrix elements, r_{31} and z_{32} , also increased in the Ge well, see Table I. These are a consequence of the larger Luttinger parameters in Ge than in Si. Although less studied than low Ge-content structures,^{13–17} high quality strain com-

TABLE I. Parameters of the strain-compensated quantum wells QW1 and QW2. I_{pump} is the intensity required to achieve the net gain of 30 cm^{-1} at the signal photon energy of E_s , when the pump photon energy was E_p . Transition energies at $k = 0$ and dipole moments (square root of the squared average over k_F) are also given.

Sample	QW1	QW2
Layers	Si/Si _{0.2} Ge _{0.8}	Si _{0.8} Ge _{0.2} /Ge
thickness (nm)	3/5	3/5
Substrate	Si _{0.5} Ge _{0.5}	Si _{0.3} Ge _{0.7}
$E_{31}, E_{\text{L2-H1}}$ (eV)	0.245	0.292
$E_{32}, E_{\text{L2-L1}}$ (eV)	0.154	0.190
$E_{\text{H1-H2}}$ (eV)	0.130	0.138
r_{31} (nm)	0.41	0.42
z_{32} (nm)	2.16	2.63
$\sqrt{r_{31}z_{32}}$ (nm)	1.02	1.17
$z_{\text{H1-H2}}$ (nm)	1.11	1.14
E_p (eV)	0.2388	0.2798
E_s (eV)	0.1573	0.1928
I_{pump} (MW cm ⁻²)	11.9	4.19

pensated Ge-SiGe structures with high average Ge content can be prepared, for example, by low-energy plasma-enhanced chemical vapor deposition method.^{6,28} As a result of the enhanced δE , the required I_p is 4.19 MW cm^{-2} to obtain the net gain of 30 cm^{-1} for E_p of 0.278 eV and E_s of 0.193 eV, Figs. 2(b) and 2(c). The I_p here is larger than the threshold excitation intensity value observed for an n -type InGaAs midinfrared Raman laser^{21,25} because of the smaller matrix elements in SiGe, especially that of the pump transition r_{13} . Still, the required I_p and the intensity absorbed in the quantum well (below $\sim 100 \text{ kW cm}^{-2}$) are well below the values which strain-compensated SiGe structure cannot withstand.²⁵ The calculated pump intensity required to obtain the net gain of $\sim 300 \text{ cm}^{-1}$ was found to be 17 MW cm^{-2} (with the differential gain of 21.5 cm/MW) with only a factor of ~ 4 higher intensity than that required for $\sim 30 \text{ cm}^{-1}$. This is because the H1-H2 absorption remains unchanged, whereas the Raman gain increases steeply with the pump intensity. Equation (1) shows that the Raman gain is proportional to the hole concentration p . However, simulations for p larger than $\sim 3 \times 10^{11} \text{ cm}^{-2}$ showed that the pump intensity required to obtain the net gain of 30 cm^{-1} decreases sub-linearly with the increase of p and saturates to $\sim 3 \text{ MW cm}^{-2}$ above $9 \times 10^{11} \text{ cm}^{-2}$. This is due to the simultaneous increase of the H1-H2 absorption-loss and the shift of E_{32} ($E_{\text{L2-L1}}$) to lower energy (hence larger absorption) at larger k .

IV. SiGe WAVEGUIDE DESIGN ON GRADED BUFFER SUBSTRATES

As reported in Ref. 14, one can design a SiGe waveguide structure on a SiGe relaxed buffer substrate prepared on a Si substrate. Fig. 3 shows one example using 250 period of QW2 as the active layer. The quantum wells are prepared on a $3.5 \mu\text{m}$ -thick stepped graded buffer on a Si substrate (terminated with a $0.5 \mu\text{m}$ -thick $\text{Si}_{0.3}\text{Ge}_{0.7}$ layer) and cladded by a $0.5 \mu\text{m}$ -thick $\text{Si}_{0.3}\text{Ge}_{0.7}$ layer. The individual barriers are tensile strained and the wells are compressively strained

FIG. 3. (a) Mode profile of a fundamental TM mode at the photon energy of 0.195 eV in a SiGe waveguide on a Si substrate with 2 μm -thick multiple Ge quantum wells (QW2) as the active layer (marked by light red box). The layers between $y = 0$ and 3.5 μm are step-graded relaxed buffer terminated by a 0.5 μm -thick $\text{Si}_{0.3}\text{Ge}_{0.7}$ layer. The active layer is capped by a 0.5 μm -thick $\text{Si}_{0.3}\text{Ge}_{0.7}$ layer. (b) Cross-sectional mode profile in a 28 μm -wide waveguide ridge of the TM mode depicted in (a).

because of the large lattice mismatch between Si and Ge. Still, one can grow such SiGe structures when the layers are strain-compensated with respect to the relax buffer substrate; for example, when the average Ge content of the unit structure (a barrier and a well) is the same as the Ge content of the relaxed SiGe layer underneath the multi-layers, as long as the thickness of the individual layers are below the critical relaxation thickness. Successful growth of such high Ge-content strain-compensated superlattices and quantum cascade structures with excellent qualities by using the low-temperature molecular beam epitaxy^{15,26,27} and the low-energy plasma-enhanced chemical vapor deposition²⁸ have been already demonstrated.

The guided mode in Figure 3 was calculated by using a finite element electromagnetic wave simulator (COMSOL Multiphysics) at the photon energy of 0.195 eV for a 28 μm -wide ridge waveguide. The 62% overlap of the fundamental TM mode with the multiple QW2 active layers with 2 μm total thickness was obtained for this design. This modal overlap can be further increased by using a Ge-cladding.¹⁴ End mirrors can be fabricated by reactive-ion etching²⁷ to form a Fabry-Perot cavity. Assuming a waveguide length of ~ 2 mm or above (with the facet reflectivity of ~ 0.3), the reflection loss at the mirror facets is estimated to be below $\sim 6 \text{ cm}^{-1}$. Since the free carrier absorption by the residual impurities with the concentration in the order of 10^{16} cm^{-3} and the absorption by phonons in the considered wavelength range are both small (below $\sim 1 \text{ cm}^{-1}$),^{25,29–31} the loss may originate from the scattering in the relaxed buffer substrate. Clarification and experimental investigation of the midinfrared waveguide loss of relaxed buffer substrates, especially those with high Ge content, require future study. Nevertheless, these consideration suggests that one can achieve transparency in the ridge waveguide SiGe Raman laser structures at the I_p values assumed for QW1 and 2 in Figs. 1 and 2, when the net gain of the active layer is in the order of $20\text{--}30 \text{ cm}^{-1}$.

V. CONCLUSION

Motivated by the quest for the integration of optics into Si electronics, considerable effort has been expended in the past to the development of an electrically pumped Si laser. As a step toward that goal, the present work proposed to study an optically pumped device and provided a design of a test device, which allows for an experimental investigation of the gain and loss with a working Si-laser, *albeit* optically pumped operation. In particular, optically pumped Si-laser structures consisting of square SiGe and Ge quantum well active layers and SiGe waveguides were considered and analyzed theoretically. With the state-of-the-art crystal growth technology for the thick strain-compensated SiGe multi-layers, it is feasible to fabricate such devices. Predicted required pump intensities to achieve transparency and lasing were moderate that can be obtained by using a standard pulsed laser system in combination of parametric conversion. Being based on square quantum wells, the linewidth broadening of the proposed pump and gain transitions by the interface-roughness scattering is minimal. Therefore, the predicted gain is likely to be more robust than previously proposed gain structures based on the transitions in the superlattice states and quantum cascade states either in valence band or in conduction band.

ACKNOWLEDGMENTS

The author acknowledges S. Fukatsu for stimulating discussions on the optical gain in Si-based structures, J. Faist for helpful discussions on the Raman gain on symmetric and asymmetric SiGe structures, and M. Scheinert and H. Sigg for discussion on asymmetric SiGe structures on low-Ge substrates. This work was partially supported by the Swiss National Foundation.

¹D. A. B. Miller, *Proc. IEEE* **97**, 1166 (2009).

²H. Rong, S. Xu, Y.-H. Kuo, V. Sih, O. Cohen, O. Raday, and M. Paniccia, *Nat. Photonics* **1**, 232 (2007).

³J. Liu, X. Sun, R. Camacho-Aguilera, L. C. Kimerling, and J. Michel, *Opt. Lett.* **35**, 679 (2010).

⁴J. E. Roth, O. Fidaner, R. K. Schaevitz, Y.-H. Kuo, T. I. Kamins, J. S. Harrier, and D. A. B. Miller, *Opt. Express* **15**, 5851 (2007).

⁵Y.-H. Kuo, Y.-K. Lee, Y. Ge, S. Ren, J. E. Roth, T. I. Kamins, D. A. B. Miller, and J. S. Harries, *Nature (London)* **437**, 1334 (2005).

⁶S. Tsujino, H. Sigg, G. Mussler, D. Christina, and H. von Känel, *Appl. Phys. Lett.* **89**, 262119 (2006).

⁷S. G. Cloutier, P. A. Kossyrev, and J. Xu, *Nature Mater.* **4**, 887 (2005).

⁸J. Bao, M. Tabbal, T. Kim, S. Charnvanichborikarn, J. S. Williams, M. J. Aziz, and F. Cappasso, *Opt. Express* **15**, 6727 (2007).

⁹Y. Yasutake, J. Igarashi, N. Tana-ami, and S. Fukatsu, *Opt. Express* **19**, 16739 (2009).

¹⁰G. Dehlinger, L. Diehl, U. Gennser, H. Sigg, J. Faist, K. Ensslin, D. Grützmacher and E. Müller, *Science* **290**, 2277 (2000).

¹¹I. Bormann, K. Brunner, S. Hackenbuchner, G. Abstreiter, S. Schmult, and W. Wegscheider, *Appl. Phys. Lett.* **83**(26), 5371 (2003).

¹²S. A. Lynch, R. Bates, D. J. Paul, D. J. Norris, A. G. Cullis, Z. Ikonik, R. W. Kelsall, P. Harrison, D. D. Arnone, and C. R. Pidgeon, *Appl. Phys. Lett.* **81**, 1543 (2002).

¹³L. Diehl, S. Mentese, E. Müller, D. Grützmacher, H. Sigg, U. Gennser, I. Sagnes, Y. Campidelli, O. Kermarrec, D. Bensahel, and J. Faist, *Appl. Phys. Lett.* **81**, 4700 (2002).

¹⁴S. Tsujino, H. Sigg, M. Scheinert, D. Grützmacher, and J. Faist, *IEEE J. Sel. Top. Quantum Electron.* **12**, 1642 (2006).

¹⁵S. Tsujino, A. Borak, E. Müller, M. Scheinert, C. V. Falub, H. Sigg, D. Grützmacher, M. Giovannini, and J. Faist, *Appl. Phys. Lett.* **86**, 062113 (2005).

- ¹⁶T. Fromherz, M. Meduna, G. Bauer, A. Borak, C. V. Falub, S. Tsujino, H. Sigg, and D. Grützmacher, *J. Appl. Phys.* **98**, 044501 (2005).
- ¹⁷S. Tsujino, A. Borak, C. Falub, T. Fromherz, L. Diehl, H. Sigg, and D. Grützmacher, *Phys. Rev. B* **72**, 153315 (2005).
- ¹⁸M. Troccoli, A. Belyanin, F. Cappasso, E. Cubukcu, D. L. Sivco, and A. Y. Cho, *Nature (London)* **433**, 845 (2005).
- ¹⁹O. Gauthier-Lafaye, P. Boucaud, F. H. Julien, S. Sauvage, J. M. Lourtioz, V. Thierry-Mieg, and R. Planel, *Appl. Phys. Lett.* **71**, 3619 (1997).
- ²⁰H. C. Liu, C. Y. Song, Z. R. Wasilewski, A. J. SpringThorpe, J. C. Cao, C. Dharma-wardana, G. C. Aers, D. J. Lockwood, and J. A. Gupta, *Phys. Rev. Lett.* **90**, 077402 (2003).
- ²¹M. Scheinert, H. Sigg, S. Tsujino, M. Giovannini, and J. Faist, *Appl. Phys. Lett.* **91**, 131108 (2007).
- ²²J. B. Khurgin, and H. C. Liu, *Phys. Rev. B* **74**, 035317 (2006).
- ²³S. Tsujino, N. Usami, A. Weber, G. Mussler, V. Shushunova, D. Grützmacher, Y. Azuma, and K. Nakajima, *Appl. Phys. Lett.* **91**, 032104 (2007).
- ²⁴K. Reimann, R. A. Kaindl, and M. Woerner, *Phys. Rev. B* **65**, 045302 (2001).
- ²⁵M. Scheinert, Ph.D. dissertation, University of Neuchatel, 2007.
- ²⁶S. Tsujino, S. Mentese, L. Diehl, E. Müller, B. Haas, D. Bächle, S. Stutz, D. Grützmacher, Y. Campidelli, O. Kermarrec, and D. Bensahel, *Appl. Surf. Sci.* **224**, 337 (2004).
- ²⁷A. Borak, S. Tsujino, H. Sigg, C. V. Falub, M. Scheinert, L. Diehl, D. Grützmacher, E. Muller, U. Gennser, Y. Campidelli, O. Kermarrec, D. Bensahel, and J. Faist, *Mater. Res. Soc. Symp. Proc.* **832**, F4.2.1 (2005).
- ²⁸M. Bonfanti, E. Grilli, M. Guzzi, M. Virgilio, G. Grosso, D. Chrastina, G. Isella, and H. von Känel, *Phys. Rev. B* **78**, 041407 (2008).
- ²⁹*Landolt-Börnstein: Numerical Data and Functional Relationships in Science and Technology - New Series*, Group III, Semiconductors, Subvolume a Vol. 17, edited by O. Madelung (Springer-Verlag, Berlin 1982), p. 389 and 404.
- ³⁰D. K. Schroder, R. N. Thomas, and J. C. Swartz, *IEEE Trans. Electron Devices* **ED-25**, 254 (1978).
- ³¹The dominant “free carrier absorption” by the carriers in the active layer is the H1-H2 intersubband absorption that was already accounted for in Figs. 1 and 2.