Room temperature photoluminescence of Ge multiple quantum wells with Ge-rich barriers

E. Gatti,[1] E. Grilli,[1] M. Guzzi,[1] D. Chrastina,[2,a)] G. Isella,[2] and H. von Känel[2]
[1]*L-NESS, Dip. di Scienza dei Materiali, Università di Milano Bicocca, via Cozzi 53, I-20126 Milano, Italy*
[2]*L-NESS, Dip. di Fisica del Politecnico di Milano, Polo di Como, via Anzani 42, I-22100 Como, Italy*

(Received 3 August 2010; accepted 23 December 2010; published online 20 January 2011)

We report on the observation of room temperature direct band gap photoluminescence in compressively strained-Ge multiple quantum wells with Ge-rich SiGe barriers. A detailed experimental study of the temperature dependence of the photoluminescence is carried out from 5 K up to room temperature. We find that the direct gap photoluminescence at room temperature is due to the thermal excitation of carriers from L-type to Γ-type confined states. Room temperature photoluminescence shows that Ge/SiGe multiple quantum wells are promising candidates for efficient light emitting devices monolithically integrated on Si. © *2011 American Institute of Physics*. [doi:10.1063/1.3541782]

The search for efficient light emitters on Si is challenging, due to the indirect bandgaps of Si and Ge. However, in Ge the indirect and direct energy minima differ by only about 140 meV at room temperature (RT),[1] providing Ge with a quasidirect gap, allowing for Ge-based photonic devices compatible with Si technology. Photodetectors made from epitaxial Ge layers on Si substrates,[2–4] optical modulators based on the Franz–Keldysh effect,[5] and optical modulators based on the quantum-confined Stark effect in strained-Ge quantum wells (QWs) (Refs. 6 and 7) have all been demonstrated. Recently, photoluminescence (PL) in tensile strained Ge/SiGe QWs and optical gain in *n*-type Ge films on Si substrates have been reported at RT.[8–10]

We have recently shown that compressively strained-Ge multiple quantum well (MQW) heterostructures grown by low-energy plasma-enhanced chemical vapor deposition (LEPECVD) (Ref. 11) display optical properties analogous to those of direct gap III-V based QWs.[12,13] Furthermore, preliminary photocurrent spectra obtained on metal-semiconductor-metal structures have shown the potential of Ge QW based detectors in Si photonics.[14] Our low temperature (LT) PL spectra showed emission due to both indirect and direct transitions,[12] and thus Ge/SiGe MQWs are expected to be interesting systems for the development of light emitters compatible with Si CMOS technology. Indeed, transient population inversion, and therefore optical gain, has been demonstrated in Ge/SiGe MQWs grown by LEPECVD.[15]

In this work we present a detailed analysis of the direct gap related PL of undoped compressively strained Ge/SiGe MQWs with Ge-rich barriers. In particular, we have studied the temperature dependence of the PL from 5 K to RT. Our data demonstrate that the direct gap PL at RT is due to the thermal excitation of carriers from L-type to Γ-type confined states.

The sample was grown by LEPECVD on a 100 mm Si(001) substrate. The first part of the structure consists of a buffer layer graded from Si to $Si_{0.1}Ge_{0.9}$ capped with a 2 μm $Si_{0.1}Ge_{0.9}$ layer, forming a fully relaxed virtual substrate (VS). The strain compensated MQW structure consists of 50 Ge QWs, 10 nm thick, with nominally $Si_{0.15}Ge_{0.85}$ barriers, 21 nm thick. A VS with the same design but without MQW layers was used as a reference sample for the transmission measurements. The optical transmission measurements were performed using a Jasco FT/IR-800 Fourier transform spectrometer equipped with an InGaAs detector. PL measurements were performed using the same spectrometer equipped with an InGaAs detector and a Peltier cooled PbS detector. The sample was excited using the 1064 nm (1.17 eV) line of a Nd:YVO_4 laser. Carriers are therefore directly photoexcited into the QWs (resonant excitation) since the photon energy is larger than the direct gap of Ge but smaller than the direct gap of the SiGe barriers. The exciting power density was about 4 kW/cm^2. The optical measurements were performed in the 5–300 K temperature range using a closed cycle cryostat. More details of the sample growth, of the QW and barrier thickness determination, and of the optical techniques are reported in Ref. 12.

Figure 1 shows the transmission spectra at 5 K and at RT. The main features of the transmission spectra are sharp excitonic transitions.[12] In Fig. 1 the high energy part of the

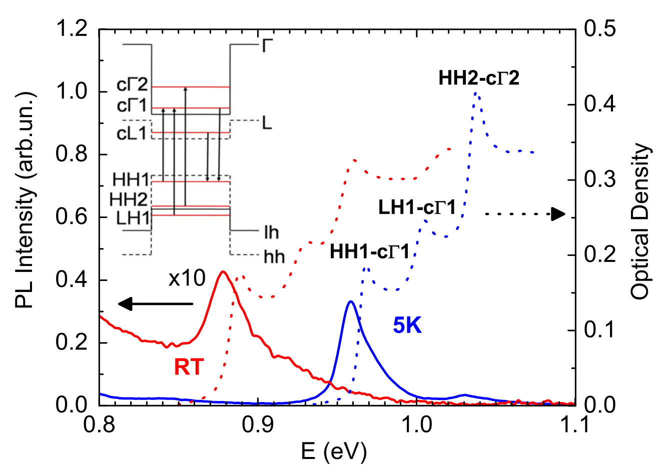

FIG. 1. (Color online) PL (full lines) and absorption (dashed lines) spectra measured at RT and at 5 K and detected by an InGaAs detector. Inset: conduction and valence band edge profiles and electron and hole confined states (energies not to scale); the transitions visible in the absorption and PL spectra are also shown.

[a)]Electronic mail: daniel@chrastina.net.

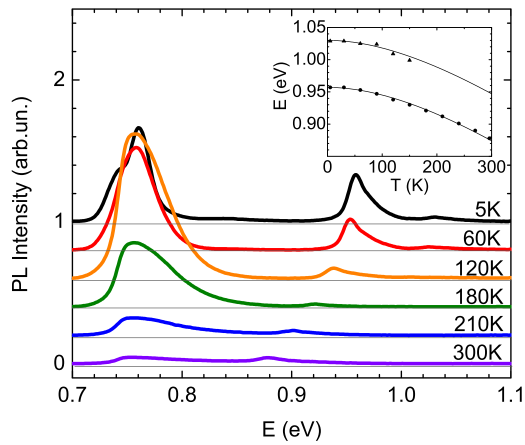

FIG. 2. (Color online) PL spectra measured between 5 K and RT. PL was detected by an InGaAs detector. Inset: peak energy of the cΓ1-HH1 and cΓ2-HH2 transitions as a function of the sample temperature, with the full lines giving the variation with temperature according to the literature parameters for the Ge bulk direct bandgap (see Ref. 16).

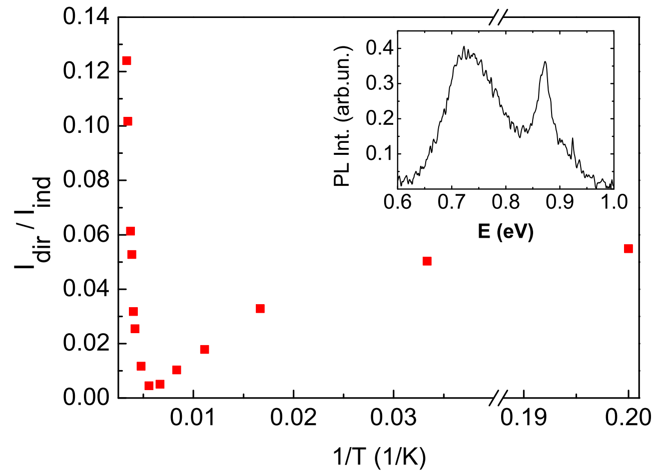

FIG. 3. (Color online) Ratio of the integrated intensity of the direct recombination (I_{dir}) and of the indirect recombination (I_{ind}) as a function of the reciprocal temperature. PL was detected by a PbS detector. Inset: the RT PL spectrum.

PL spectra measured at the same temperatures is also shown, with a strong peak at about 0.96 eV at LT and at about 0.88 eV at RT. In the inset the conduction and valence band edge profiles and the electron and hole confined states are shown.[12] The comparison between absorption and emission spectra leads to the attribution of this high energy structure to the dipole allowed cΓ1-HH1 recombination involving the $n=1$ conduction state at Γ (cΓ1) and the heavy-hole $n=1$ valence state (HH1). The cΓ1-HH1 recombination at the two temperatures is characterized by an intense high energy tail. At 5 K a second peak appears on the tail at about 1.030 eV that can be attributed to the cΓ2-HH2 transition, as demonstrated by the comparison of PL and absorption spectra. These high energy transitions have been reported for other systems such as GaAs/AlGaAs MQWs (Ref. 17) and GaInNAs/GaAs QWs.[18] The cΓ1-LH1 transition, which involves the $n=1$ light-hole state (LH1) is not visible in the spectrum. This may be due to the smaller dipole matrix element of LH→cΓ transitions as compared to HH→cΓ transitions.[13,19] In the PL spectra this weak transition is superimposed on the high energy tail of the cΓ1-HH1 recombination.

PL spectra measured at different temperatures are reported in Fig. 2. Two main features dominate the spectra: the first feature, peaked at about 0.96 eV at 5 K, is attributed to the direct cΓ1-HH1 transition, and the second, at about 0.76 eV, to the indirect cL1–HH1 transition.[12] Increasing the temperature, the cΓ1-HH1 transition shifts toward lower energies, as expected. At the same time, its intensity decreases up to about 180 K and then, for higher temperatures, markedly increases again. In the inset of Fig. 2 the cΓ1-HH1 and cΓ2-HH2 transition energies are reported as a function of the sample temperature; the cΓ1-HH1 and cΓ2-HH2 transitions vary in temperature in the same way as the direct bandgap of bulk Ge as calculated using literature parameters (full curves).[16] The calculated curves closely follow the experimental data, showing that the sample is not significantly heated by the exciting laser. In Fig. 2 the strong intensity decrease observed at about 0.73 eV on the low energy tail of the cL1–HH1 indirect transition is due to the cutoff of the InGaAs detector's spectral response. The actual shape of indirect gap related PL peak was obtained using the PbS detector. As an example, the inset of Fig. 3 shows the spectrum measured at RT. The sharp peak at about 0.875 eV is due to the direct cΓ1-HH1 transition and the broad band centered at about 0.72 eV is due to the indirect transition involving the $n=1$ L-type confined state (cL1–HH1).[12] As mentioned above, the Nd:YVO_4 laser excites carriers resonantly into the Γ-type confined states, from which they can recombine with holes confined in the Γ-type states, giving rise to the direct cΓ1-HH1 transition in the LT PL spectra. Furthermore, electrons can be very efficiently transferred from the Γ to the L-type confined states by fast mechanisms, mainly scattering with emission of phonons,[15,20] which produces the indirect cL1–HH1 transition in the LT PL spectra.

Figure 3 reports the ratio between the PL integrated intensity due to direct recombination (I_{dir}) and that due to the indirect recombination (I_{ind}) as a function of the reciprocal temperature. PL spectra were measured using a PbS detector. Increasing the temperature, the I_{dir}/I_{ind} ratio slowly decreases up to about 180 K and then markedly increases. These data demonstrate the presence of two different regimes. The I_{dir}/I_{ind} ratio decreases as temperature increases due to increased Γ-L scattering, since the increased phonon population enhances Γ-L scattering by both emission and absorption of phonons. The marked increase of the I_{dir}/I_{ind} ratio at temperatures above about 180 K strongly suggests that carriers are thermally promoted from L to Γ-type states. Neglecting the temperature dependence of the direct and indirect radiative recombination efficiencies, the activation energy ΔE for the L to Γ excitation can be estimated from the data in Fig. 3. ΔE should be compared with the energy difference $\Delta E_{\Gamma L}$ between the Γ and L-type $n=1$ confined states. $\Delta E_{\Gamma L}$ at LT can be obtained from Fig. 3 of Ref. 12: for a cΓ1-HH1 transition energy of $E_{\Gamma}=0.96$ eV the cL1–HH1 transition energy is $E_L=0.76$ eV (in agreement with the LT spectra in Fig. 2). Taking into account the temperature dependence of the direct[16] and indirect[1] energy gap of bulk Ge, we can estimate $\Delta E_{\Gamma L}=190\pm 10$ meV at RT. An evaluation of the slope from the data points at higher temperatures in Fig. 4 gives $\Delta E=170\pm 9$ meV, in reasonably good agreement with $\Delta E_{\Gamma L}$. Thermal quenching of the PL (see Fig. 2) means that spectra with a reasonable signal-to-noise ratio

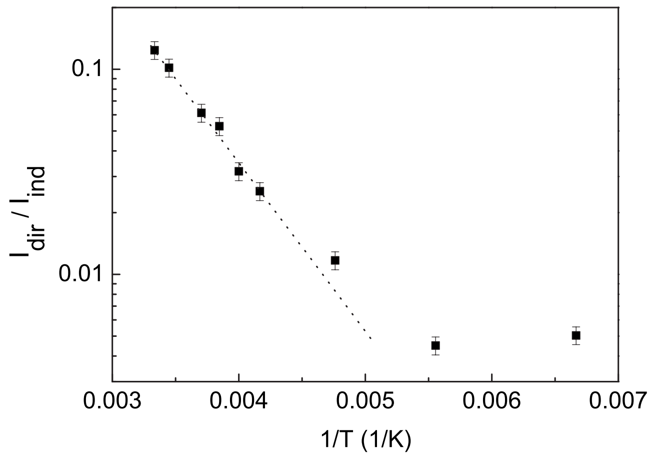

FIG. 4. Ratio of the integrated intensity of the direct (I_{dir}) and indirect (I_{ind}) recombination as a function of the reciprocal temperature for $T>180$ K. PL was detected by a PbS detector. The slope of the straight line gives an activation energy $\Delta E = 170 \pm 9$ meV.

cannot be measured above RT, so that ΔE cannot be more accurately obtained.

The thermal excitation of carriers from L-type to Γ-type confined states at high temperatures is confirmed by measuring the PL spectra with a nonresonant excitation, i.e., using the frequency doubled 532 nm (2.33 eV) line of a Nd-YVO_4 laser with photon energy higher than the barrier energy gap. At high temperatures the PL spectra measured both by exciting resonantly and nonresonantly show direct and indirect transitions. At LT, however, direct transitions are present only for resonant excitation. For nonresonant excitation the electrons, which are photogenerated mainly in the barriers, thermalize by reaching the L-type confined states, which are the lowest available states in energy, without significantly populating any Γ-states. Only at higher temperature can Γ-states be populated by means of thermal excitation from L.

In conclusion, we have presented a detailed experimental analysis of the temperature dependence of direct gap related PL of Ge compressively strained MQWs with Ge-rich barriers grown on Si(001) by LEPECVD. We find direct gap PL at RT and show that the RT PL is due to the thermal excitation of carriers from L-type to Γ-type confined states. These results open perspectives for promising applications of Ge/SiGe MQWs in light sources monolithically integrated on Si.

The authors gratefully acknowledge Matteo Bonfanti for his experimental support in the first phase of this work. This work was partially supported by Cariplo Foundation through the MANDIS Project and by Italian MIUR through the PRIN 2008 project 20085JEWJ2.

[1]*Landolt-Börnstein: Numerical Data and Functional Relationships in Science and Technology—New Series*, edited by O. Madelung (Springer, Berlin, 1982), Vol. III/17a.
[2]D. D. Cannon, J. Liu, D. T. Danielson, S. Jongthammanurak, U. U. Enuha, K. Wada, J. Michel, and L. C. Kimerling, Appl. Phys. Lett. **91**, 252111 (2007).
[3]D. Ahn, C. yin Hong, J. Liu, W. Giziewicz, M. Beals, L. C. Kimerling, J. Michel, J. Chen, and F. X. Kärtner, Opt. Express **15**, 3916 (2007).
[4]J. Osmond, G. Isella, D. Chrastina, R. Kaufmann, M. Acciarri, and H. von Känel, Appl. Phys. Lett. **94**, 201106 (2009).
[5]S. Jongthammanurak, J. Liu, K. Wada, D. D. Cannon, D. T. Danielson, D. Pan, L. C. Kimerling, and J. Michel, Appl. Phys. Lett. **89**, 161115 (2006).
[6]Y.-H. Kuo, Y. K. Lee, Y. Ge, S. Ren, J. E. Roth, T. I. Kamins, D. A. B. Miller, and J. S. Harris, Nature (London) **437**, 1334 (2005).
[7]P. Chaisakul, D. Marris-Morini, G. Isella, D. Chrastina, X. L. Roux, E. Gatti, S. Edmond, J. Osmond, E. Cassan, and L. Vivien, Opt. Lett. **35**, 2913 (2010).
[8]Y. Chen, C. Li, Z. Zhou, H. Lai, S. Chen, W. Ding, B. Cheng, and Y. Yu, Appl. Phys. Lett. **94**, 141902 (2009).
[9]Y. Chen, C. Li, H. Lai, and S. Chen, Nanotechnology **21**, 115207 (2010).
[10]J. Liu, X. Sun, L. C. Kimerling, and J. Michel, Opt. Lett. **34**, 1738 (2009).
[11]G. Isella, D. Chrastina, B. Rössner, T. Hackbarth, H.-J. Herzog, U. König, and H. von Känel, Solid-State Electron. **48**, 1317 (2004).
[12]M. Bonfanti, E. Grilli, M. Guzzi, M. Virgilio, G. Grosso, D. Chrastina, G. Isella, H. von Känel, and A. Neels, Phys. Rev. B **78**, 041407(R) (2008).
[13]M. Virgilio, M. Bonfanti, D. Chrastina, A. Neels, G. Isella, E. Grilli, M. Guzzi, G. Grosso, H. Sigg, and H. von Känel, Phys. Rev. B **79**, 075323 (2009).
[14]M. Bonfanti, E. Grilli, M. Guzzi, D. Chrastina, G. Isella, H. von Känel, and H. Sigg, Physica E **41**, 972 (2009).
[15]C. Lange, N. S. Köster, S. Chatterjee, H. Sigg, D. Chrastina, G. Isella, H. von Känel, M. Schäfer, M. Kira, and S. W. Koch, Phys. Rev. B **79**, 201306(R) (2009).
[16]Y. Yin, D. Yan, F. H. Pollak, M. S. Hybertsen, J. M. Vandenberg, and J. C. Bean, Phys. Rev. B **52**, 8951 (1995).
[17]Y. T. Oh, S. K. Kim, T. W. Kang, C. Y. Hong, J. J. Lee, H. K. Lee, and T. W. Kim, Solid State Commun. **93**, 629 (1995).
[18]S. Shirakata, M. Kondow, and T. Kitatani, Phys. Status Solidi A **203**, 2680 (2006).
[19]G. Bastard, *Wave Mechanics Applied to Semiconductor Heterostructures* (Éditions de Physique, Les Ulis Cedex, France, 1988).
[20]X. Mu, Y. J. Ding, Z. Wang, and G. J. Salamo, Laser Phys. **15**, 225 (2005).