# Two-dimensional photonic crystals with germanium on insulator obtained by a condensation method

Thi-Phuong Ngo,[1] M. El Kurdi,[1] Xavier Checoury,[1] Philippe Boucaud,[1,a)] J. F. Damlencourt,[2] O. Kermarrec,[3] and D. Bensahel[3]
[1]*Institut d'Electronique Fondamentale, CNRS-Univ Paris-Sud 11, Bâtiment 220, 91405 Orsay, France*
[2]*CEA-DRT-LETI, 17 Rue des martyrs 38054 Grenoble Cedex 9, France*
[3]*STMicroelectronics, Rue Jean Monnet 38054 Crolles, France*

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Germanium on insulator on silicon substrates can be obtained by the growth of a SiGe layer on silicon on insulator followed by a condensation at high temperature and a Ge epitaxial growth. We show that these substrates can be used for photonic devices. Two-dimensional photonic crystals with defect cavities have been fabricated. The emission at room temperature of condensed germanium can be spectrally controlled by varying the lattice parameter of the photonic crystals. Resonant emission is obtained between 1400 and 1700 nm when modifying the lattice periodicity between 400 and 480 nm for L3 cavities in a triangular lattice. Quality factors of 540 are obtained for the fundamental mode of the L3 cavity around 1600 nm. The experimental radiation pattern of the defect cavities is compared to the one calculated by a finite-difference time-domain method. A specificity of the germanium-on-insulator photonic crystals is that the optical sources are distributed within the whole material, by opposition to photonic crystals with a single quantum dot layer internal source. © *2008 American Institute of Physics*. [DOI: 10.1063/1.3054332]

There is a growing interest in pure germanium on the silicon platform for microelectronics or photonics applications. One of the main interest of pure germanium for photonics is linked to the photodetection at 1.3 or 1.55 $\mu$m. In microelectronics, pure Ge field effect transistors are particularly attractive because of the enhanced electron and hole mobilities. Some of the recent progress in photonics and microelectronics has been achieved because of the availability of silicon-on-insulator (SOI) substrates that can reduce substrate leakage. Substrates of pure germanium-on-insulator on silicon are also available. Their advantages are the compatibility with the silicon technology and the subsequent cost reduction as compared to a bulk Ge substrate technology.

There are different methods to obtain germanium-on-insulator substrates. The first method is based on the same wafer bonding technique that is used to obtain silicon-on-insulator substrates. A thin pure germanium layer is transferred via oxide bonding onto a silicon substrate using the Smart-cut™ technology. This method can provide wafers with a good homogeneity on a large scale. One of its drawback is that it is not well adapted for the ultrathin or localized integration of pure germanium. A second method to obtain germanium-on-insulator substrates was recently introduced by Tezuka *et al.*[1] It is based on a condensation method. A SiGe layer is first epitaxially grown on a SOI substrate with a thin silicon upper layer. High temperature oxidation leads to a Ge enrichment of the upper layer since the oxide layers act as a barrier for Ge diffusion. Pure germanium on insulator can then be obtained by this technique.

The germanium-on-insulator substrates have been mainly developed for their applications in microelectronics.[2] Localized integration of pure germanium is very interesting for *n* and *p* type metal oxide semiconductor field effect transistor technology. Fewer works have been devoted to their photonic applications despite the strong interest to use germanium either for its absorption or emission properties. A lateral superlattice in germanium on insulator has been proposed for electrically pumped lasing at 1.55 $\mu$m.[3] The crossover from indirect to direct band structure is also expected for tensily strained germanium that is expected to lead to promising developments for photonics applications.[4] We have recently shown that two-dimensional photonic crystals could be fabricated with germanium-on-insulator substrates.[5] The latter were obtained by the wafer bonding of a thin pure germanium layer on a SOI substrate. The optical properties of these crystals were however limited by the thickness of the buried oxide (170 nm).

In this work, we show that germanium-on-insulator substrates obtained by a condensation method can be useful for photonics applications. This potential is illustrated through the study of two-dimensional photonic crystals. We show that the near-infrared emission of condensed germanium can be measured at room temperature. We have investigated L3 cavities obtained by omitting to drill three air holes along one direction in a triangular lattice. The emission associated with the fundamental mode of the L3 cavity is observed. The resonant emission is controlled and tuned between 1400 and 1700 nm by varying the photonic crystal lattice parameter. The radiation pattern of the photonic crystal cavity is compared to the one obtained by finite-difference time-domain modeling.

The fabrication of the germanium-on-insulator substrate was achieved through the following sequence.[6,7] In a first step a 75 nm thick $Si_{0.9}Ge_{0.1}$ layer was deposited using chemical vapor deposition on a standard SOI substrate with an upper silicon layer that has been thinned down to a 20 nm thickness. This layer is then capped with a 2 nm thick Si layer in order to avoid the Ge consumption during the oxidation. A high temperature oxidation is then performed, lead-

a)Electronic mail: philippe.boucaud@ief.u-psud.fr. URL: http://pages.ief.u-psud.fr/QDgroup/index.html.

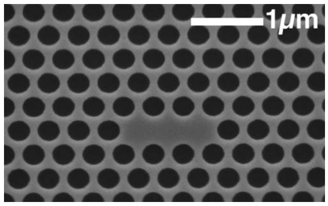


FIG. 1. Scanning electron micrograph of a L3 cavity fabricated on the germanium on insulator on silicon substrate. The lattice periodicity is 420 nm.

ing to a 10 nm thick pure Ge layer on insulator (GeOI). The Ge layer is epitaxially thickened to get a 170 nm thick layer. Cyclical thermal annealing was then performed followed by a mechanochemical polishing of the surface. The buried oxide thickness of the GeOI substrate is around 440 nm. The lattice parameter of the Ge film was measured by x-ray diffraction cartography. The perpendicular lattice parameter is slightly smaller (0.18 %) than the one of relaxed Ge thus indicating that a very small tensile strain is present in the layer.

The fabrication of the photonic crystals was performed with the same processing techniques, which are used for the silicon-based photonic crystals containing GeSi self-assembled islands.[8–10] A 300 nm thick photoresist (ZEP520A) was first deposited on the sample. A triangular lattice pattern and elongated cavities were defined by electronic beam lithography. The pattern was then transferred into the germanium layer down to the buried oxide by reactive ion etching using $SF_6$ and $CHF_3$ gases. The air hole radius $r$ is around $0.36a$, where $a$ is the lattice periodicity. Figure 1 shows a scanning electron micrograph image of a L3 microcavity. The optical properties were measured using a microphotoluminescence setup at room temperature. The sample is illuminated by the 488 nm line of an argon ion laser through an objective with a 0.8 numerical aperture. At this wavelength, the Ge absorption coefficient is very large ($>100\,000\ \mathrm{cm}^{-1}$) and all the incident light is absorbed in the Ge layer. The photoluminescence is collected by the same objective, dispersed by a monochromator with a 600 lines/mm grating and recorded either with a nitrogen-cooled InGaAs multichannel photodiode or a nitrogen-cooled Ge photodiode.

Figure 2(a) (top) shows the photoluminescence of a L3 cavity with a lattice periodicity of 420 nm (log scale). The emission can be easily observed at room temperature indicating than the thin layers are of high quality. The emission is significantly enhanced as compared to the photoluminescence of the unprocessed sample. A rough estimate of the power level radiated by the cavity indicates that it is of the order of 10 pW. The luminescence exhibits different resonances and is dominated by a broad resonance at 1533 nm. The corresponding normalized frequency of this resonance $u=a/\lambda$ is 0.274. A resonance with a smaller amplitude and a smaller linewidth is observed on the low energy side at 1597 nm. The corresponding normalized frequency of this resonance $u=a/\lambda$ is 0.263. Its linewidth is 3 nm corresponding to a quality factor $Q=\omega/\Delta\omega \sim 540$. This resonance corresponds to the fundamental mode of the L3 cavity. Similar quality factors around 500 have been reported on SOI substrates when the thickness of the buried oxide is 1 $\mu$m, larger than the one in the present structure.[11] It indicates that in the weak absorption region, photonic crystals with

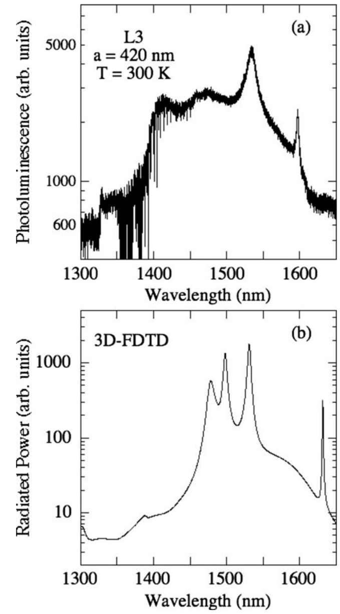


FIG. 2. (a) (Top) Room temperature photoluminescence of a L3 cavity with a triangular lattice periodicity of 420 nm (log scale). The fundamental mode is observed at 1597 nm. The incident excitation power is 1 mW. (b) (Bottom) Finite-difference time-domain simulation of the photonic crystal cavity radiated pattern recorded at normal incidence with a numerical aperture of 0.8 (log scale).

germanium-on-insulator substrates have similar properties than those fabricated on SOI substrates with a thin buried oxide. Like in SOI structures, the small thickness of the buried oxide and the asymmetry of the structure, which induces coupling between TE and TM polarizations, limits the value of the quality factor. The reported quality factor is also similar to the one reported for germanium-based ring resonators on SOI.[12] We have calculated the far-field radiation pattern of the cavity by finite-difference time-domain simulations. A specificity of photonic crystals fabricated with germanium-on-insulator substrates is that the internal emitters are distributed all over the dielectric slab. It thus significantly differs from the case where only a single layer of GeSi islands is inserted in the middle of the slab[10] since a larger number of optical modes can be excited. We have therefore performed three-dimensional finite-difference time-domain calculations of the far-field radiation pattern of the cavity with a large density of embedded optical sources within all the germanium volume. The phases of the optical sources are chosen randomly in order to avoid coherent effects.[13] 1200 point sources within a volume of $4000 \times 4000 \times 170\ \mathrm{nm}^3$ were considered. The vertical stacking consists of the Ge layer, the oxide layer and the silicon substrate. The refractive index of the Ge layer was taken equal to 4. The calculated radiated pattern perpendicular to the photonic crystal layer is shown in Fig. 2(b) (log scale). The radiated power is collected perpendicular to the surface within a 0.8 numerical aperture. In the simulation, the absorption losses associated with the Ge direct band gap above 1550 nm are not taken into account. Several resonances are observed on the spectra. At low energy, the fundamental mode is predicted at 1630 nm in close agreement with the experimental observation. The difference might be accounted for by a small decrease in the Ge refractive index. The calculated quality factor of this mode is 1500, larger than the one experimentally observed. Several factors can explain this difference. As reported in Ref. 10, the free-

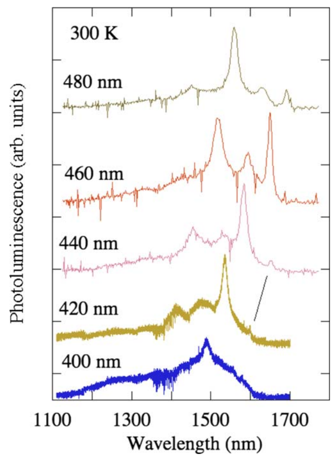


FIG. 3. (Color online) Room temperature photoluminescence of L3 cavities for different triangular lattice periodicities. The curves have been offset for clarity. The incident excitation power is 2 mW. The lattice periodicities are indicated on the graph. The shift of the fundamental mode is highlighted.

carrier absorption associated with the photoinduced carriers can decrease significantly the experimental quality factors measured by room temperature photoluminescence. For a 2 mW incident excitation power, the quality factor of the fundamental mode decreases down to 300. While the quality factor at a very weak excitation power cannot be accurately measured because of the small signal to noise ratio, it is clear that the free-carrier absorption contributes to the decrease in the quality factor. The bulk absorptions of Ge associated with the indirect and direct band gap also contribute to the decrease in the quality factor. This feature is strongly dependent on the wavelength and absorption amplitude. Finally, roughness, disorder and deviations from ideal parameters might also contribute to the deviation between modeling and experimental measurements. It is interesting to note that the calculated quality factor remains higher than the one calculated for a L3 cavity on SOI with a 1 $\mu$m thick oxide.[11] There is a difference between germanium-on-insulator substrates and SOI substrates. As the Ge index is larger than the index of silicon, there is always a truly guided mode for quasi-TE polarization, independently of the oxide thickness. For SOI substrates, as the index of the upper layer is identical to the one of the substrate, the fundamental TE-like slab mode becomes leaky and coupled to the radiative continuum if the oxide thickness is too thin. GeOI substrates on silicon are thus more interesting for guiding with thin oxide layers. A group of three resonances are predicted at 1530, 1496, and 1477 nm. The 1530 resonance corresponds to the 1533 resonance experimentally observed. The next two resonances are those observed around 1470 nm. We note that the amplitude ratio of the radiated modes differs from the amplitudes observed experimentally. The main difference stems from the absorption of the Ge layer, which is not taken into account in the calculation. This absorption broadens the resonances and significantly decreases their amplitudes, as will be shown below in the measurements as a function of the lattice parameter.

Figure 3 shows in linear scale the room temperature emission of L3 cavities for different lattice parameters. The curves have been measured with two different detectors, an InGaAs photodetector for the 400 and 420 nm lattices and a Ge photodiode for the 440, 460, and 480 nm lattices. The cutoff of the InGaAs photodetector is around 1600 nm. The Ge photodiode has a larger sensitivity at long wavelength despite its cutoff and thus allows to follow the different peaks on a larger scale. The resonances shift as expected to long wavelength as the lattice parameter is increased. The fundamental mode of the L3 cavity can be observed at 1650 nm for the 440 nm lattice, i.e., at a normalized frequency of 0.266. The normalized frequency of the resonances increases slightly as the lattice parameter is increased because of the change in refractive index and of the modal dispersion of the slab waveguide as a function of the wavelength. The fundamental mode is not observed for the larger lattice parameters because of the detector cutoff. The spectral position of the resonances at higher energy than the fundamental mode can be easily followed. The effect of the bulk germanium absorption is directly observed. As the resonances shift to long wavelength, the bulk absorption decreases and the peak amplitude increases.[5] For example, the full width at half maximum of the resonance at 1455, 1519, and 1560 nm corresponding to the 440, 460, and 480 nm lattice periodicities decreases from 38 to 28 and 16 nm. The increase in the quality factor from 38 to 54 and 98 can be accounted for by the absorption coefficient $\alpha$ of the germanium layers at the resonance wavelengths, which is of the order of 1000–4000 cm$^{-1}$ according to $Q=2\pi n/\alpha\lambda$. The spectra shown in Fig. 3 indicate that the room temperature germanium emission can be tuned over a large range between 1400 and 1700 nm by changing the photonic crystal lattice parameter. This tunability results from the broad emission of Ge at room temperature associated with the direct band gap and from the high excitation density. The spectra also indicate the good optical quality of the GeOIs obtained by the condensation method. At long wavelength, the detector cutoff limits the investigation of a larger tunability. These results demonstrate that germanium-on-insulator substrates obtained by the condensation method are promising candidates to fabricate Ge resonant cavity devices for photonics applications in the near infrared.

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