Thin Solid Films 613 (2016) 64–67

Contents lists available at ScienceDirect

Thin Solid Films

journal homepage: www.elsevier.com/locate/tsf

Study of the light emission in Ge layers and strained membranes on Si substrates

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ARTICLE INFO

Article history:
Received 6 July 2015
Received in revised form 16 November 2015
Accepted 17 November 2015
Available online 18 November 2015

ABSTRACT

The influence of pattern design and tensile strain on light emission was investigated in Ge layers and suspended membranes. The optical properties were examined by micro-photoluminescence and reflectivity. Tensile strain was extracted from micro-Raman spectroscopy. It has been shown that Fabry–Pérot interference fringes can dominate the photoluminescence spectra. It is crucial to remove them in order to analyze the photoluminescence changes coming from tensile strain; especially if Fabry–Pérot oscillations are in the same energy range compared to the stress-induced spectral shift. This study highlights the fact that this interference must be taken into account in order to examine the strain in suspended Ge layers.

1. Introduction

Integrating laser sources which are compatible with microelectronics is a major challenge in silicon photonics. To overcome the indirect nature of the Ge bandgap, n-type doping, tensile strain or Sn alloying has been proposed to fabricate low-threshold Ge-on-Si lasers [1–3]. For the strain approach, thick Ge layers grown on Si (001) substrates are naturally tensile-strained due to the difference in thermal expansion coefficients between Ge and Si that comes into play during cooling to room temperature. Membrane patterning has thus been used to focus and locally amplify the tensile strain in Ge [4,5]. Tensile strain in Ge devices may also be induced either externally [6] or by using SiN layers stressors [7,8].

Ge photoluminescence (PL) is enhanced when the crystal is tensile-strained [4,5,9,10]. However, the PL enhancement factor due to applied tensile strain is difficult to accurately quantify [4] for Ge membranes, particularly if the finite thickness of the Ge layer gives rise to Fabry–Pérot interferences (FPI) in the same energy range as the red shift due to the tensile strain. In order to reduce interferences, very thick (28 µm) [6] or ultra-thin Ge layers (24 nm) [11] can be used. They are however not fit for photonics applications which typically require a Ge thickness of around 0.35 µm, corresponding to the condition for monomode light propagation at a 2 µm wavelength. Anti-reflection (AR) coatings have been proposed to solve this problem, but without quantification of the PL enhancement [12].

We study here the impact of tensile strain on Ge membrane light emission by taking into account the influence of FPI and we quantify the effect of an AR coating. Firstly, the emission spectrum and the reflectivity of a suspended Ge layer are simulated numerically. Then, the influence of FPI on PL spectra is investigated experimentally, at first in Ge layers grown on bulk Si or Silicon-On-Insulator (SOI) substrates, without strain variations. Results from strained Ge membranes will be then detailed for uniaxial (~1.2%) and biaxial (~0.5%) tensile strains. Finally, the impact of an AR coating is quantified.

2. Modeling

In order to evaluate the impact of the FPI on the PL spectrum of a Ge membrane, the emission and the reflection spectra of a suspended Ge layer have been calculated by finite difference time domain calculations using Rsoft software. Fig. 1(a) shows the simulated system: a 1 µm-thick Ge layer ($n_{Ge} = 4.1$ [13]) is embedded in air ($n_{air} = 1$) and the detection cell is placed above, at a distance $h_d > 1$ µm. A broad band light source is positioned at a distance h_s. The normal reflectivity of the suspended layer has been calculated using $h_s > h_d$. The emission properties have been calculated by integrating the detected spectra for $0 < h_s < 1$ µm to obtain what we called the calculated flat PL spectrum. This is an image of PL if the generated carriers are homogeneously distributed in a layer with an isoenergetic emission. The impact of FPI on PL emission can then be evaluated using this theoretical approach. Fig. 1(b) shows the resulting flat PL and reflectivity spectra. Since the refractive index contrast between air and Ge is high, a very high fringe contrast is found. The flat PL maximum is those localized at the reflectivity minimum (*e.g.* close to 0.76 eV).

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http://dx.doi.org/10.1016/j.tsf.2015.11.039

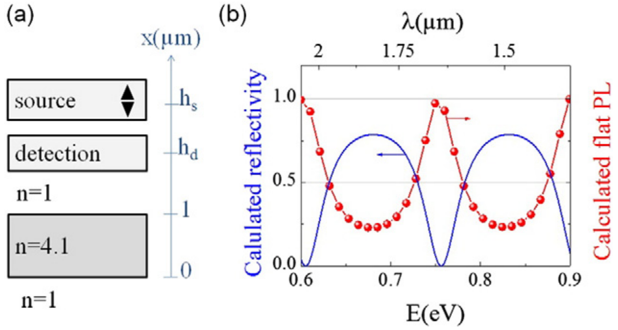

Fig. 1. Reflection and emission modeling: (a) model design and (b) corresponding calculated reflectivity (solid line) and calculated flat normalized PL spectrum (dots).

3. Photoluminescence of Ge layers

PL measurements were performed on Ge layers grown on bulk Si or thin SOI substrates. Since the refractive index contrast is lower for Ge on Si than for Ge on SOI, we expect the impact of FPI on PL to be smaller for Ge grown on Si than for Ge on SOI. Fig. 2(a–c) shows the PL spectra measured on *in-situ* phosphorous doped (10^{19} cm^{-3}) Ge layers grown on bulk Si or on thinned-down optical SOI substrates. The Ge layer grown on bulk Si(001) is 0.7 ± 0.2 μm-thick and the Ge layer grown on SOI is 1.4 ± 0.2 μm-thick (starting Si thickness: close to 60 nm; buried SiO_2 thickness: 2 μm). Both Ge layers were grown at 400 °C, 13 kPa using GeH_4 and PH_3 gaseous precursors in an Epi Centura Reduced Pressure-Chemical Vapor Deposition machine. The tensile strain in bulk Ge layers at the end of the fabrication process is around 0.2% resulting from differences in thermal expansion coefficients between Ge and Si. Room temperature (RT) PL measurements were performed using a Horiba iHR 320 spectrometer with a 5 mW green pump laser focused to a 5 μm-diameter spot. The emitted PL signal was collected with an optical fiber, sent through the spectrometer and detected with an extended InGaAs photo-detector. In addition, macroscopic reflectivity measurements (~4 mm^2 measured surface) were carried out in a Bruker IFS55 Fourier transform infrared spectrometer with a Tungsten input lamp and an InSb cooled detector.

Several measurements were performed at different locations of the 200 mm wafers: the Ge layer thickness decreases slightly when moving from center to the edges (±0.2 μm). The influence of Ge thickness on PL can easily be seen by changing the pump spot location. For Ge layers grown on bulk Si (Fig. 2(a)), Ge thickness variations have little effect on the spectrum shape. The Γ and L valley emissions are close to 1.65 μm and 1.8 μm, respectively, in good agreement with theoretical data [3]. However, thickness variations of Ge layers grown on SOI have a major impact on PL spectra because of the presence of Fabry–Pérot oscillations (coming from the high index contrast between Ge and SiO_2) (Fig. 2(b)). The actual shape of the Ge emission can be extracted by fitting the maximum PL signal over all the measured thicknesses (Fig. 2(c)), which results in a thickness-independent PL spectrum with the Γ and L valley emissions at the correct energies.

We have seen in the previous section that FPI shapes the emission and the reflectivity of the Ge layer. In order to study this effect, Fig. 2(d) and (e) show normalized reflectivity spectra and the associated PL spectra measured for different thicknesses of the Ge layer grown on SOI. As expected, a good agreement is found between the energies of PL maxima and reflection minima, which confirm experimentally that the PL spectral shape is strongly dominated by FPI, as can also be seen in the layer stack reflectivity. Note that this effect is highly dependent on the measurement method. Indeed, the detected oscillation contrast will depend on the numerical aperture of the measurement setup.

4. Strain induction by membrane processing

Ge membranes were processed in the 0.7 ± 0.2 μm thick Ge layer grown on Si presented above to locally enhance the strain. Membrane patterning was performed by ultra-violet lithography followed by dry etching in an inductively coupled plasma reactor. Ge membrane under-etching was conducted in a tetramethyl ammonium hydroxide 25% solution at 60 °C. Fig. 3(a) and (b) present the membrane designs for uniaxial and biaxial stress induction, respectively. The angle "a" is fixed at 26°. Tensile stress was tuned by changing the parameters x, d and the under-etching which is measured by Scanning Electron Microscopy (SEM) imaging using a Zeiss Ultra 55 apparatus at 15 kV operating voltage. Finite Element Method simulations using COMSOL Multiphysics were performed using a 2D linear elastic model assuming no stress along the direction perpendicular to the membrane plane. We clamped the pattern away from the region of structuration and applied the initial stress on the free standing membrane. Fig. 3(c) and (d) shows the results of simulations for both designs. In the case of the micro-cross design, the

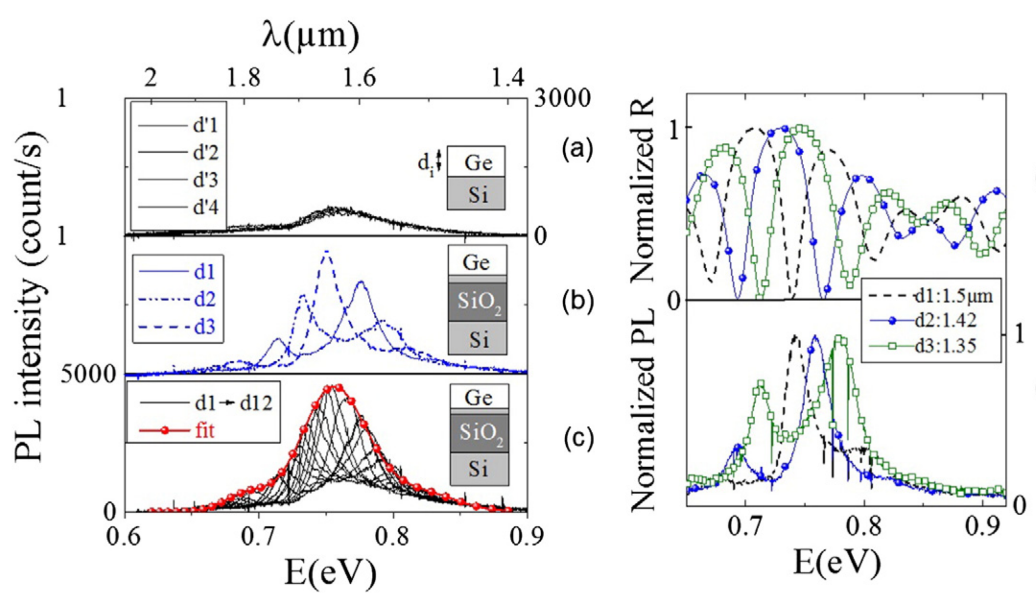

Fig. 2. Room temperature photoluminescence spectra measured in (a) Ge grown on Si, and (b,c) Ge on SOI; (d) normalized reflectivity and (e) corresponding photoluminescence measured in Ge on SOI (d_i: Ge layer thicknesses).