Pushing the limits of silicon transistors

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ABSTRACT

In this work we study Ge transistor structures grown on silicon substrate. We use photoluminescence to determine the band gap of Ge under tensile strain. The strain is induced by growing Ge on an InGaAs buffer layer with variable In content. The band energy levels are modeled using a 30 band k·p model based on first principles calculations. Photoluminescence measurements show a reasonable correspondence with calculated values of the band energies.

Keywords: Ge photoluminescence, tensile Ge, Ge InGaAs, Ge Si, Ge TFET, silicon photonics, biaxial strain Ge, Ge k.p

1. INTRODUCTION

Potential increases in transistor clock speeds are limited by heat dissipation on chip [1], [2]. This dissipation can be reduced, for example, by selecting transistor channel materials with low threshold voltage and high charge carrier mobility. A good candidate to replace Si as a suitable channel material is Ge [3], [4]. Tensile strained Ge has a significantly higher n-type mobility [5], which has a profound impact on the transistor switch rate.

Laser-on-chip integration for a wide range of applications requires laser manufacturing compatible with Si-based technology. However there are certain challenges. Firstly, Si itself is not a direct band gap material and is therefore an inefficient light emitter. The absence of lasers on Si is a significant problem for optical integration in CMOS. Secondly, most conventional III-V materials typically have a large lattice mismatch and different thermal expansion coefficients from Si [6]. In the case of direct growth of such III-V materials on silicon, they suffer from a high-density of threading dislocations and thus have a limited suitability for laser applications, though there are a few reports on GaAs-based lasers grown on a Si substrate [7]. An alternative method would be using Ge as a laser material. Under tensile strain, the bottom of the Ge Γ-valley decreases in energy faster than the L-valley, thereby potentially making Ge a direct bandgap semiconductor. However when grown directly on silicon, Ge is compressively strained. In order to achieve tensile strain one needs to grow a buffer with a larger lattice parameter than that of Ge. GaAs is nearly lattice matched to Ge (-0.12% of mismatch). By adding In in to the GaAs buffer, one can increase the lattice constant of the InGaAs layer and thus induce a biaxial tensile strain to the Ge. In this work, the energy positions of the Γ and L valleys of Ge grown on InGaAs buffers with different In content are studied by means of photoluminescence spectroscopy.

2. THEORETICAL CALCULATIONS

The Ge band alignment grown on InGaAs depends on the InGaAs layer surface termination (figure 1). If the InGaAs surface is terminated on the As atomic layer, the Ge valence band has a lower band edge than that of InGaAs. The valence band offset is 0.12 eV for Ge on $In_{0.13}Ga_{0.87}As$ and 0.10 eV for $In_{0.17}Ga_{0.83}As$. In this case, band alignment between Ge and InGaAs is type II. However if the InGaAs surface is terminated on the Ga or In atomic layer, the Ge valence band is higher than that of the InGaAs layer, leading to a type I band alignment. We calculate the Ge band structure within a 30 band k.p formalism, based on GW calculations [8], [9]. The different energy transitions as a function of strain in the Ge layer are presented in figure 2. The blue and red lines correspond to the L and Γ band minima, respectively. Under tensile strain, the degeneracy of the light-holes and heavy-holes at the zone center split. The solid and dashed lines correspond to light-hole (lh) and heavy-hole (hh) transitions respectively. To avoid strain relaxation in the material, the Ge layers are grown below the critical thickness: 40nm and 30nm for the lower and higher strain structures, respectively. Quantum confined energy levels in these thin layers are shown in figure 2 as dot and dash-dot lines. The experimentally measured values of Γ-hh and L-lh energy transitions are also presented in the figure for

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approximate values of 0.8% and 1.1% tensile strain. According to the band energy calculations Ge should switch band gap type from indirect to direct under a 1.5% biaxial tensile strain.

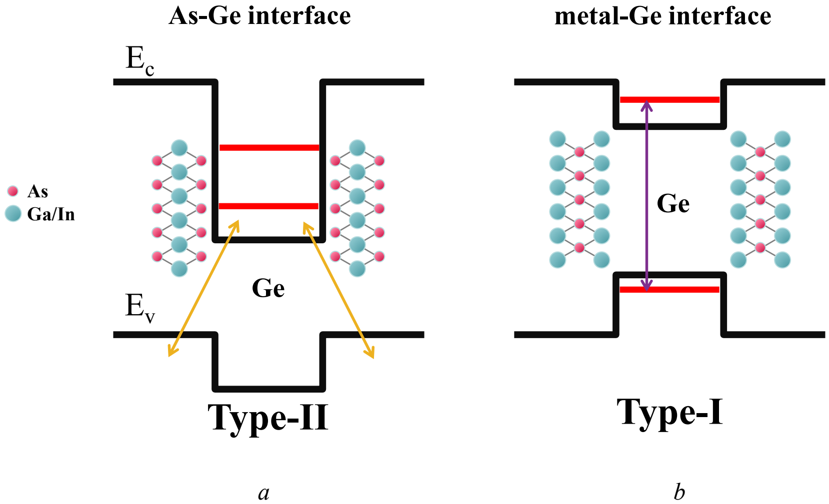

Figure 1. Ge Band alignment for various InGaAs surface orientation. *a* – As-terminated, *b* –metal-terminated.

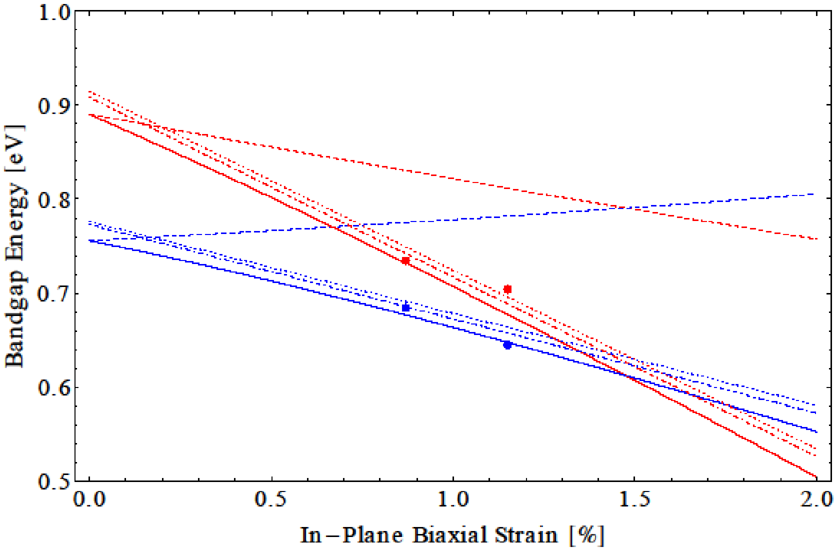

Figure 2. Ge L and Γ band energy calculations. Energy transitions are depicted: L-lh – blue solid line, Γ-lh – red solid line, L-hh – blue dashed line, Γ-hh – red dashed line. Electron energy levels for 30 nm quantum well: dash-dot and dot lines. Experimental peak points: red and blue dots.

3. SAMPLES DESCRIPTION

We performed an optical study of the multilayer transistor structures, presented in figure 3. They are grown on a Si substrate, followed by a GaAs layer and an $In_xGa_{1-x}As$ linear-graded barrier with a slow increase of In-content. Samples presented in this paper have a gradient of up to 13% and 17% In content. On the top of the $In_{0.13}Ga_{0.87}As$ and $In_{0.17}Ga_{0.83}As$ layers there are a 40 nm and 30 nm layers of Ge, respectively. Lattice mismatch between $In_{0.13}Ga_{0.87}As$ and Ge is 0.8% (sample *a*) while between $In_{0.17}Ga_{0.83}As$ and Ge it is 1.1% (samples *b* and *c*), hence defining a corresponding level of biaxial tensile strain in Ge. A thick layer of highly strained Ge could suffer from lattice relaxation. In order to examine the effect of strain relaxation on device performance, a sample with a higher In component has been grown with an InGaAs cap layer above Ge(sample *c*) and without it (sample *b*) for comparison. Complete growth details of tensile strained Ge are described in the previous work [10].

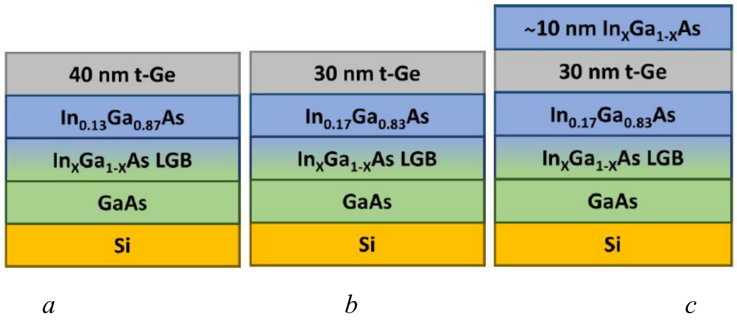

Figure 3. Samples material structure with a – 0.8%, b – 1.1%, c – 1.1% tensile strain applied to Ge

4. EXPERIMENTAL SETUP

For material characterization, we performed photoluminescence spectroscopy measurements of the samples as shown in figure 3. A Ti:Sa pulsed laser was used as the excitation source, tuned to 800nm with 80 MHz repetition rate, 300 fs pulse width and 0.55 W average power. Laser and photoluminescence light were respectively focused and collimated by the CaF_2 lens in a confocal optical system. The laser spot was focused on a 9µm diameter, providing 860 kW/cm^2 of pump power density. Samples were chilled in a closed-cycle He cryostat down to 7.5 K. Photoluminescence was separated from the pump laser beam by a dichroic mirror and focused by a CaF_2 mirror to a monochromator with a grating blazed at 2 µm. Emission from the InGaAs layer was filtered by a 1300 nm long pass filter. Photoluminescence was detected by an extended InGaAs detector with a sensitivity range from 1.2 µm to 2.6 µm (~0.5-1 eV).

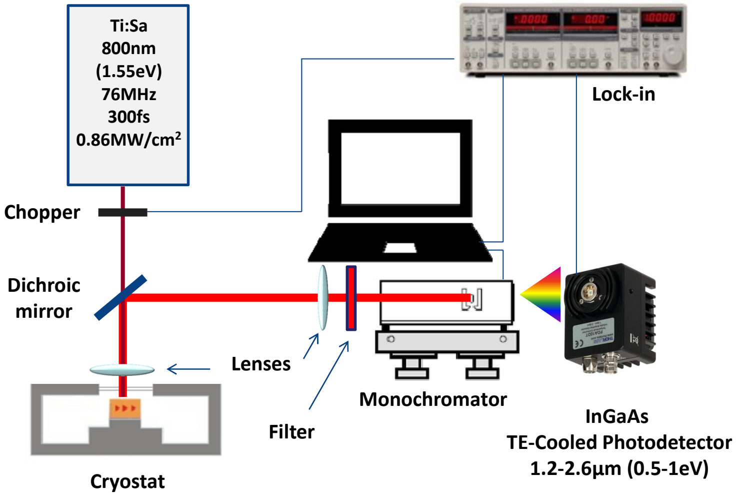

Figure 4. Photoluminescence spectroscopy setup

5. RESULT DISCUSSION

The measured photoluminescence spectrum of sample *a* is presented in figure 5. It is fitted with 3 Gaussian peaks, representing the Γ-lh, L-lh and Type II energy transitions. From the experiment, the Γ-lh transition is at 0.74 eV and the L-lh transition is at 0.68 eV. Calculations for a 40nm layer of Ge under ε=0.8% tensile strain gives values of 0.68 eV and 0.74 eV for the L-lh and Γ-lh transition energies, respectively. These values are 0.01eV above the band edges due to quantum confinement of electrons in the thin layer of Ge. The calculated values match a Gaussian approximation of the measured values, presented in figure 5. The calculated valence band offset between As terminated InGaAs layer and Ge is 0.12 eV, so the small Gaussian peak around 0.62 eV corresponds to a Type II transition from the Ge Γ conduction band valley to the InGaAs valence band. The presence of this peak confirms that the InGaAs layer is As-terminated during the growth process.

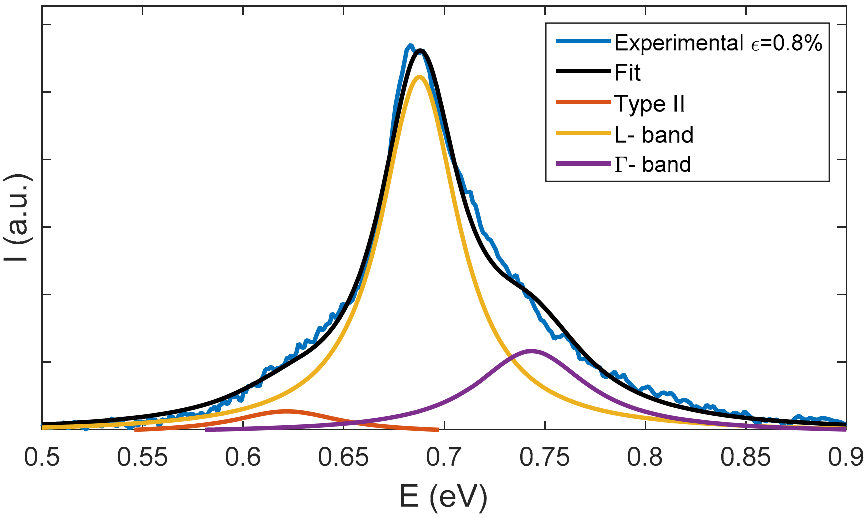

Figure 5. Sample *a* photoluminescence spectrum. Blue line corresponds to experimental data, black line – three peak Gaussian approximation. Purple line corresponds to Type II transition from Ge conduction band to InGaAs valence band; dark yellow line corresponds to L-lh transition; orange line corresponds to Γ-lh transition

For sample *b,* under ε=1.1% tensile strain, the photoluminescence spectrum is presented in figure 6. There is a clear shift of photoluminescence to lower energies for this sample in comparison to sample *a* under ε=0.8% tensile strain (figure 5). A Gaussian approximation with 3 peaks at 0.71 eV, 0.64 eV and 0.60 eV is fit to the experimental data, corresponding to the Γ-lh, L-lh and Type II transition energies. Calculated band edges of Ge under ε=1.1% tensile strain are 0.65eV for L-lh transition and 0.68 eV for Γ-lh transition. There is a 0.04eV difference for Γ-lh transitions between the fitted and calculated values. We speculate that this is due to strain relaxation of the Ge layer as well as broad nature of photoluminescence around Γ-lh transition peak. The valence band offset is calculated to be 0.10eV. The small peak around 0.60 eV again represents a Type II transition from the Ge Γ-valley conduction band to the InGaAs valence band.

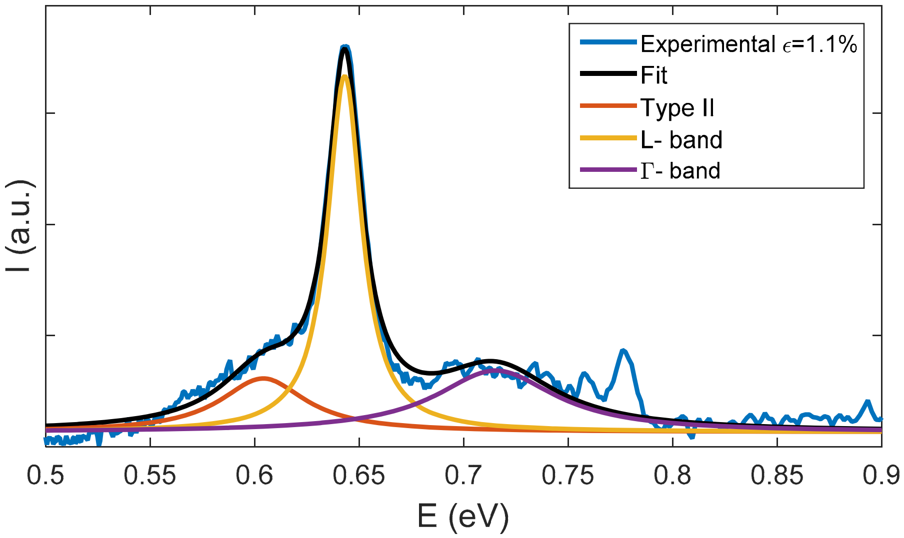

Figure 6. Sample *b* photoluminescence spectrum. Blue line corresponds to experimental data, black line – three peak Gaussian approximation. Purple line corresponds to Type II transition from Ge conduction band to InGaAs valence band; dark yellow line corresponds to L-lh transition; orange line corresponds to Γ-lh transition

In an effort to minimise the effect of strain relaxation in the Ge layer a thin InGaAs layer was deposited on the top of Ge for sample *c*. Emission from this sample is presented in figure 7 fitted using a Gaussian approximation with three peaks at 0.7 eV, 0.64 eV and 0.60eV. The peak position of the spectra is consistent with that of sample b. However the fitted peak position of the Γ-lh transition has shifted 0.1eV to lower photon energies from 0.71 to 0.7 eV, consistent with a lower strain relaxation in the Ge layer. However, it is still 0.02eV higher than the calculated values indicating some level of strain relaxation in Ge.

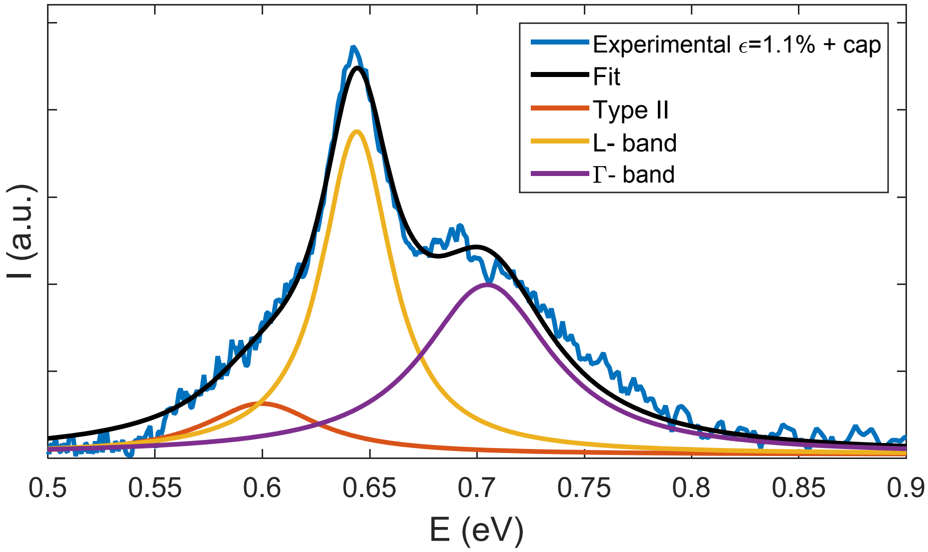

Figure 7. Sample *c* photoluminescence spectrum. Blue line corresponds to experimental data, black line – three peak Gaussian approximation. Purple line corresponds to Type II transition from Ge conduction band to InGaAs valence band; dark yellow line corresponds to L-lh transition; orange line corresponds to Γ-lh transition

6. CONCLUSIONS

In this paper we present photoluminescence measurements of tensile strained Ge TFET structures under high power excitation with photoluminescence photon energy detected down to 0.55 eV. To our knowledge these are the lowest photon energies reported from biaxial strained Ge thin layer. Tensile strain was applied to Ge by growth on an InGaAs buffer layer with variable In content. We observed emission red-shifts with increases in tensile strain of the Ge layer. This emission mainly corresponds to Γ-lh and L-lh energy transitions, however the presence of Type II transitions from Ge to InGaAs also indicate As terminated growth of the InGaAs layer.

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