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Room-temperature electroluminescence from tensile strained double-heterojunction Germanium pin LEDs on Silicon substrates

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ABSTRACT

In this work, electroluminescence from the intrinsic Germanium layer of tensile strained Germanium LEDs is observed at room temperature. The pin LEDs are fabricated by low temperature molecular beam epitaxy with a double-heterojunction process on Silicon substrates. The tensile strain is adjusted at 0.24% with an annealing step at 700 °C leading to a lowering of the direct band gap. Electroluminescence spectra show a value of 0.781 eV for the direct band gap or an infrared shift of 19 meV. Increasing of the intrinsic layer thickness leads to higher electroluminescence intensity.

1. Introduction

As the research in the integrated Silicon photonics advances in providing reasonable detectors, modulators and waveguide structures, there is still the search going on for a corresponding integrated light source [1]. Germanium would be a possible material as it is already used for optical detectors integrated in the Silicon platform. But Silicon and Germanium are both indirect semiconductors and therefore in its basic form ill-suited light sources due to the low radiation efficiency. However the band structure of Germanium can be engineered to improve the direct radiative recombination since the direct band gap of Germanium is located at 0.8 eV, which is only 136 meV higher than the indirect band gap [2].

It is shown that with a tensile strain of Germanium, the direct and indirect band gap shifts to lower energies. As the shifting of the direct band gap is stronger, there is a crossing point at around 1.8% tensile strain resulting in a band-engineered direct behaving Germanium [3].

Another possibility to reduce the direct band gap is the *n*-type doping of the Germanium layer. This method enhances the occupation probability of the states at the direct band gap and increases therefore the electron concentration [4,5].

An approach with a Germanium–Tin alloy is also possible, as a certain Tin amount also decreases the direct band gap [6,7]. With a Tin amount of 10% it is shown that Germanium becomes a direct semiconductor.

In this paper we want to focus on the tensile strained approach by means of annealing the Germanium layer after the deposition. We present a series of tensile strained double-heterojunction Germanium pin light emitting diodes (LEDs) on a Silicon substrate grown with different thicknesses of the intrinsic layer. A comparison of the electroluminescence spectra is made to evaluate the influences of the tensile strain and the thickness of the intrinsic layer.

2. Layer growth and strain engineering

The layers are deposited using a 6 inch solid source molecular beam epitaxy (MBE) system at very low growth temperatures on (100) Silicon substrates with a specific sheet resistance of >1000 Ω cm [8]. At first a thermal cleaning in the MBE at 900 °C takes place removing the native oxide. Then a 100 nm buffer layer of Silicon is deposited at 600 °C providing the high quality foundation for the following active diode layers. The Silicon atoms are evaporated by an electron beam evaporator due to the high reactivity of molten Silicon. Germanium and the doping materials Sb and B are evaporated from effusion cells. The flux is monitored by a quadrupol mass spectrometer.

The diode structure starts with the deposition of a 400 nm Silicon layer at 600 °C doped with a B concentration of 10^{20} cm^{-3}. A 100 nm equally doped Germanium layer is deposited at 330 °C and annealed afterwards forming the ultra thin virtual substrate (VS). The annealing temperature must be close to the Germanium melting point to form a relaxed and smooth Germanium VS. The VS is necessary to adjust the different lattice constants of Silicon and Germanium enabling a Germanium lattice and a low defect density for the following Germanium layers [9]. These two layers form the buried layer for the ground contact.

Then an intrinsic Germanium layer is deposited on top of the virtual substrate. The intrinsic Germanium features a low

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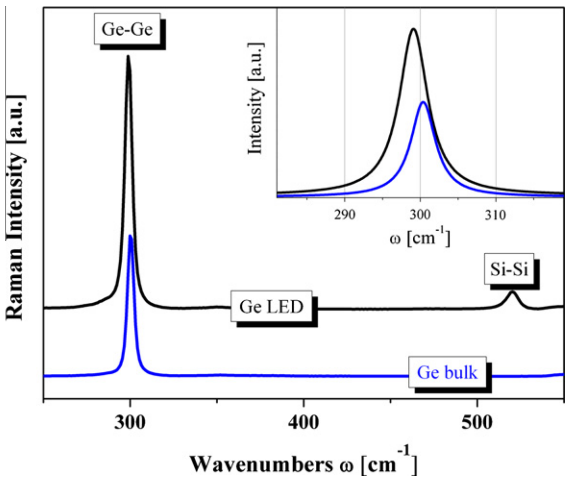

Fig. 1. μ-Raman measurements of bulk Germanium compared to the presented LED with a 700 nm intrinsic layer.

background doping of around 10^{16} cm^{-3}, which is *p*-type. Four samples with layer thicknesses d_i of 300 nm, 500 nm, 700 nm and 900 nm are made to evaluate the electroluminescence signatures of the LEDs.

The tensile strain is measured using μ-Raman spectroscopy in a backscattering setup. The laser must have the ability to penetrate the intrinsic region, thus the chosen wavelength of the laser is 633 nm. As calibration substrate Silicon and Germanium wafers are used. The Raman laser is directed in the optical window of the processed LEDs determining the strain for each device and assigning said strain to the corresponding electroluminescence spectrum. Germanium bulk is used as reference material. The signals from μ-Raman spectroscopy in the optical window of the LED with d_i = 700 nm and of Germanium bulk material are shown in Fig. 1. The Germanium–Germanium phonon peak of the LED shifts compared to the bulk Germanium from 300.5 cm^{-1} to 299.5 cm^{-1} lowering the value of about 1 ± 0.2 cm^{-1}. This value corresponds to the desired residual tensile in-plane strain of about (0.24 ± 0.05)%. As the laser beam passes the top hetero contact layer, also a weak Silicon–Silicon phonon peak is observed.

After the intrinsic layer deposition the wafers are annealed at 700 °C enabling tensile strain in the intrinsic Germanium layer. The cooling speed of Germanium layers is higher than for Silicon layers. Therefore the Germanium layer adjusts its lattice constant to the hot Silicon layer and becomes tensile strained.

A hetero top contact layer which consists of a 100 nm Germanium and a 110 nm Silicon layer with a Sb-doping of 10^{20} cm^{-3} on top of the intrinsic layer finish the LED structure. The growth of the top layers requires low temperature of 160 °C to achieve abrupt doping transition and to suppress the Sb segregation. The hetero contact is designed for optimal light transmission with the used passivation oxide. The schematic cross-section of the LED is shown in Fig. 2.

3. Device fabrication

After the MBE process, the samples are cleaned in Aceton, Isopropanol and Oxygen plasma. The photodetectors are realized as mesa diodes, so the top contact mesa and the buried layer mesa are structured by using inductively coupled plasma-reactive ion etching (ICP-RIE) in HBr plasma. A passivation layer of a 270 nm thick SiO_2 layer is deposited afterwards by PECVD with Silane. The oxide layer passivates the mesa surface and insulates the later formed Aluminum top contacts from the mesa side walls and the Silicon well edges. The top layer stack of Germanium, Silicon and SiO_2 is modeled accordingly to enhance the light transmission from the intrinsic layer at a wavelength of 1550 nm due to the decreasing refractive indices and matching thicknesses [10]. A double etch step combining RIE and BHF etching is used to open the contact windows without damaging the semiconductor surface. In the end an 1800 nm thick Aluminum is sputter deposited and structured with a double etch-step combining ICP-RIE in Cl_2 plasma and H_3PO_4 etching leaving the surface of the passivation layer undamaged and removing the Aluminum from the side walls completely. The SEM picture of one processed diode is shown in Fig. 3. The circular LEDs offer different radii of 5–80 μm enabling various input current densities.

4. Measurement

First, the operation range of the devices is defined by on-wafer DC measurements with four contact probes at room temperature. The diodes are operated at high forward currents up to 1 A. Therefore smaller structures (active mesa radius) lead to desired higher current densities while decreasing the current densities in the contact layers as well as the applied voltage. It is necessary to keep the currents in the contact layers as low as possible preventing a strong heating of the devices and its possible destruction. The heating also complicates the analysis of the electroluminescence spectra due the changing series resistance (decreasing with higher temperatures) and temperature dependency of the direct and indirect band gap.

The current densities over the applied voltage of the LEDs with a circular mesa radius of 10 μm and 80 μm are shown in Fig. 4. No differences in the forward regime of the *J–V* curves are observed for the different thicknesses of intrinsic layers. The diodes with 10 μm and 80 μm radius are operated up to 50 kA/cm^2 and

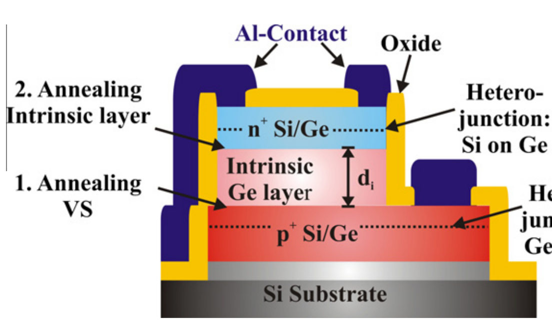

Fig. 2. Schematic cross-section of the device indicating important processing steps.

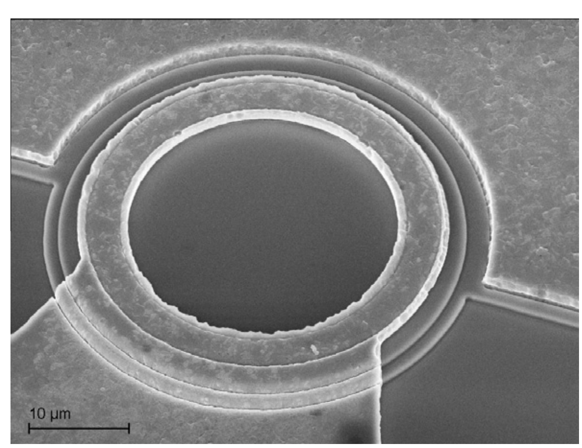

Fig. 3. A plan view SEM picture of the processed device.