Tuning the electro-optical properties of germanium nanowires by tensile strain

Supplementary information

J. Greil¹, A. Lugstein¹*, C. Zeiner¹, G. Strasser¹, E. Bertagnolli¹

¹ Institute of Solid State Electronics, Vienna University of Technology, Floragasse 7, A-1040 Vienna, Austria
*Corresponding author. Email: alois.lugstein@tuwien.ac.at

Device fabrication and NW synthesis:
A diced SOI wafer with highly p-doped (<140mΩcm) (110)-oriented device layer is structured by photolithography and reactive ion etching to form freestanding pads with {111}-faceted sidewalls. The buried oxide is partly etched wet chemically using buffered HF. Succesively the sample is introduced into a wet thermal oxidation reactor to cover the whole device in 200nm silicon oxide. The thin oxide film prevents from parasitic shunt resistance. The oxide is again patterned by photolithography and wet chemically etched to form contact regions for the nanowire and electrical contacts. Succesively gold colloids with a diameter of 30nm in aqueous solution are placed on the {111} oriented sidewall facet by dielectrophoresis. Ge NWs are synthesized by VLS growth in a hot wall CVD reactor using GeH₄ as a precursor.

The device chip is glued onto a steel plate using epoxy. The chip is aligned to have the NW <111> growth direction in parallel to the longitudinal direction of the steel plate. Electrical contacts are formed by aluminum wire bonding. To perform strain experiments, the steel substrate – SOI stack is introduced into our micromechanical 3-point loading module. By means of a micrometer screw the steel substrate is deflected, uniaxially stressing the NW in the logitudinal <111> growth direction. The amount of stress can be adjusted via the position of the micrometer screw.
**Measurement conditions:**
All of the measurements presented in the letter were performed at room temperature.

**NW FET synthesis and characterization:**
NWs are dispersed on a highly doped silicon substrate with an oxide layer on top. Contacts to the NW are formed by electron beam lithography, metal deposition and lift-off. The substrate and the two NW terminals are connected as gate, source and drain, respectively. Transfer characteristics are recorded with a semiconductor analyzer and do show increasing conductance with negative gate bias, indicating p-type field effect response of the NW channel.

**Raman setup:**
A confocal μRaman setup (Alpha300, WITec) is employed in backscattering geometry with a grating monochromator and CCD camera (DV401_BV, Andor). The excitation laser at 532nm is polarized in the NW axis and focused to a diffraction limited spot of ~500nm diameter. Power density is chosen to have negligible laser heating effects in the NW.

**Photocurrent spectroscopy:**
White light from a broadband laser source (SuperK Extreme, NKT) is fiber-coupled to a monochromator (SuperK Select, NKT), its output is polarized in the NW axis and focused on the sample with power densities on the order of 10W/cm$^2$. A current amplifier (Keithley 428) and lock-in detection is used to record the spectra.

**Fitting of the photocurrent spectra:**
The sub-bandgap tails are fitted with an exponential function and data points are extracted at a fixed EQE level EQE$_{0\%}$. EQE$_{0\%}$ is defined as the function value of the fit for 0% strain at the wavelength of 1550nm corresponding to the nominal bulk Ge $\Gamma_1$-bandgap of 0.8eV (see suppl. figure 1).
Suppl. figure 1. Extraction of spectral shift as a function of strain from the photocurrent spectra. Data points are taken at the intersection of the fit functions with the EQE=\(\text{EQE}_{0\%}\) line, satisfying the condition that the fit of the unstrained Ge-NW spectrum being \(\text{EQE}_{0\%}\) at the wavelength of the bulk Ge \(\Gamma_1\)-bandgap (1550nm).

Ripples in the photocurrent spectra:
The recurring ripples in the photocurrent spectra are attributed to a combination of diffraction at surface structures and multiple internal reflections within the SOI stack. Comparative measurements on NWs grown under the same conditions, but dispersed on a plain oxide substrate and electrically contacted using metal lift-off were performed. Since they exhibit smooth spectra (see suppl. figure 2), apart from noise at low signal levels, we conclude that our specific device structure induces the ripples in the strain device spectra.

Suppl. figure 2. Photocurrent spectrum of a single Ge NW on oxide substrate with nickel contacts.
**Time-dependent current measurements:**
When sampling current over time at a constant bias voltage and applied strain we observe no systematic variation in resistance. Suppl. figure 3 shows the measurement of a Ge-NW at a bias voltage of 1V.

**Suppl. figure 3.** Current as a function of time at 1V bias voltage under strained conditions. The black line indicates a 30 point moving average filter.