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Extended Abstracts of the 2012 International Conference on Solid State Devices and Materials, Kyoto, 2012, pp662-663

Tuning the electro-optical properties of nanowires by applying uniaxial and ultra-high strain

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1. Introduction

Strained silicon on silicon-germanium substrates was explored in an effort to boost carrier mobility since the early 1990s. In only a few short years, both, localized tensile as well as compressive strain was being deliberately introduced in a variety of ways to enhance carrier mobility in high performance devices.

Further a novel approach was predicted to achieve a direct band gap in germanium, and hence optical emission in this technologically important group-IV element by applying tensile strain along the (111) direction [1].

Thus in particular nanowires attracted a lot of attention for two reasons. First, their geometrical smallness facilitates the fabrication of novel devices which can easily be incorporated into existing fabrication lines. Second, the stiffness of NWs should enable the proposed ultra-high strain levels.

2. General Instructions

In this paper we present an approach for electrical and electro-optical characterization of individual semiconductor nanowires under ultra-high tensile strain conditions. The measurements were performed on single crystalline vapor-liquid-solid grown silicon, germanium and gallium arsenide nanowires, monolithically integrated into a micromechanical 3-point strain module (see Figure 1).

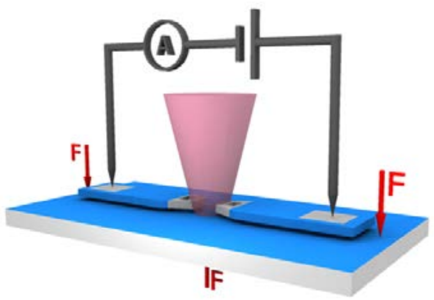

Fig. 1 3-point straining module enabling in-situ electrical and optical characterization of heavily strained nanowires.

Pure uniaxial stress is applied along the <111> growth direction of individual nanowires while at the same time performing electrical and optical characterization. Raman spectroscopy and nanofocussed synchrotron X-ray diffraction of these structures enables us to quantify and spatially resolve the strain distribution in individual nanowires.

We observed an anomalously high and negative-signed piezoresistive coefficient for silicon [2] and germanium nanowires (see Figure 2).

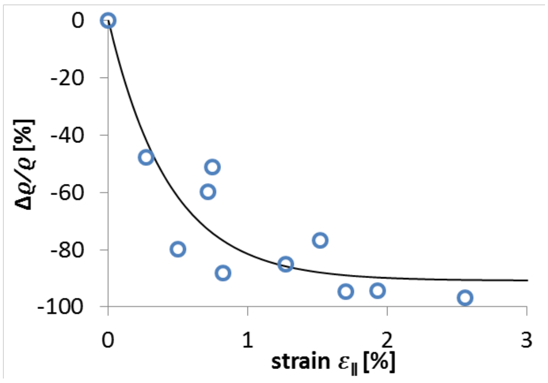

Fig. 2 Relative changes in resistivity $\Delta\rho/\rho_0$ vs. strain of the ⟨111⟩ oriented Ge nanowires.

Spectrally resolved photocurrent characterization on strained nanowires gives experimental evidence on the strain-induced modifications of the band structure. Thus photocurrent spectra reveal a red-shift in the direct bandgap energy with strain. In germanium nanowires e.g., at the maximum tensile strain of 2.6%, resistivity decreased by a factor of 30 and the direct bandgap energy was reduced by 88meV (see Figure 3).

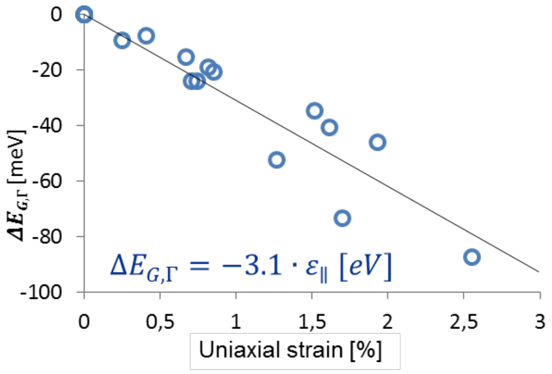

Fig. 3 Reduction of the bandgap energy of strained Ge nanowires.

For GaAs nanowires monolithically integrated in the 3-point straining module we present strain dependent micro-photoluminescence spectra.

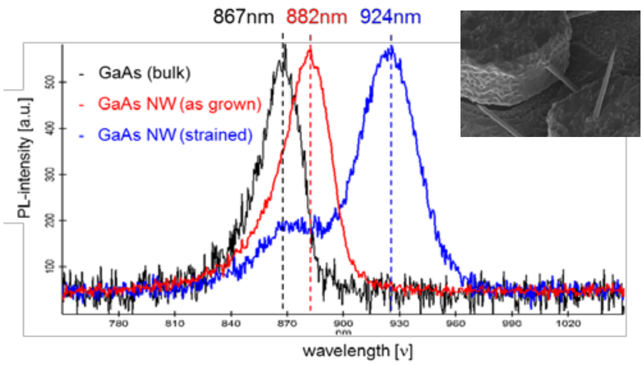

Fig. 4 Comparison of PL spectra of bulk GaAs, GaAs nanowire and a strained GaAs nanowire. The inset shows the GaAs nanowire monolithically integrated into the Si based straining module.

We have further analyzed the effect of strain on the resistivity by means of numerical simulation. The two dominant strain effects considered were a change in mobility and bandgap narrowing. Our simulations clearly show that for Si nanowires at room temperature even a considerably reduced bandgap does not give any relevant contribution of the minority carriers to the total current. The same holds, if carrier lifetimes are varied by a few orders of magnitude. This means, current remains unipolar and the reduction in resistivity can only be attributed to a mobility increase, and not to the onset of a bipolar conduction mechanism. The simulations performed indicate that the resistivity characteristics mainly reflect the strain-dependent hole mobility, and that the current measured is unipolar and space charge limited.

3. Conclusions

Individual stressed nanowires are recognized as an ideal platform for the exploration of strain-related electronic and optical effects with applications in high performance nano-optoelectronic devices.
Closing, strain engineering involves just smoothly deforming the material and strained nanowires would be a semiconductor that has a tuneable resistivity and/or bandgap while keeping its other unique characteristics. There is a vast geometric and orientational parameter space over which the electro-optical properties can be tuned, and it is unlikely that the nanowire geometries, orientation and doping parameters studied here will prove optimal for e.g. maximum piezoresistive response. While the anomalous piezoresistive phenomenon obtained in ultra-strained Si and Ge nanowires may pave the way towards sensitive, silicon compatible strain gages or high performance nanoelectronic devices, these effects should apply to many substances beyond Si. With respect to the optical properties such tuning of bandgap and thereby emission wavelength will enable novel sensor or light emitting devices.

Acknowledgements

This work is partly funded by the Austrian Science Fund (Project No. 20937-N14) and the Austrian Society for Micro- and Nanoelectronics. Technical Support by USTEM TU-Wien is gratefully acknowledged.

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