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Electrical properties and strain distribution of Ge suspended structures

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ABSTRACT

Germanium membranes and microstructures of 50–1000 nm thickness have been fabricated by a combination of epitaxial growth on a Si substrate and simple etching processes. The strain in these structures has been measured by high-resolution micro-X-ray diffraction and micro-Raman spectroscopy. The strain in these membranes is extremely isotropic and the surface is observed to be very smooth, with an RMS roughness below 2 nm. The process of membrane fabrication also serves to remove the misfit dislocation network that originally forms at the Si/Ge interface, with benefits for the mechanical, optical and electrical properties of the crystalline membranes.

1. Introduction

Crystalline membranes have a number of advantages over amorphous materials: the greater structural integrity of a crystal means that thinner, less massive, structures can be used for the same mechanical strength; the surface tends to be smoother; and there is the possibility to epitaxially grow complete device structures on the platform. Germanium is a logical supplement to enhance existing Si technologies, as its material behaviour is very similar, and allows new and improved functionality [1]. Ge has potential in spintronic [2], optical detection [3] and lasing [4] and is an accommodating buffer for III–V materials making it an excellent platform for photonic devices [5]. Germanium wafers cost approximately ten times more than silicon wafers. They are also brittle and heavier than Si ones, which hinders their technological development. Many of these problems can be overcome by growing a thin Ge layer epitaxially on a bulk Si wafer [6]. Recently, thin (<1 μm) freestanding Ge membranes [7] and various other suspended structures [8] have been fabricated through relatively simple processing. Such structures have shown that electro- and photoluminescence are affected by further tensile straining a Ge membrane [7,9,10]. Straining Ge for direct bandgap transition is a new hot topic and has been accomplished either by process-induced strain, whereby a layer with a high difference in thermal expansion, such as Si_3N_4, is deposited at elevated temperature and on cooling imparts strain to the Ge [11], or by a global platform via growth of Ge on a material with larger lattice constant, such as Ge_xSn_{1-x} alloys [12,13]. As an alternative route, creating suspended structures and hence decoupling the Ge from its substrate means that low temperature processing can mechanically strain Ge at the nano-scale and on-chip optical functions normally reserved for III–V materials can be switched to Ge without the need for other more complicated straining techniques to mature.

2. Germanium membrane fabrication

Due to the large 4.2% lattice mismatch between Ge and Si only a few monolayers of Ge can be grown pseudomorphically on Si (001). Thicker layers will relax to the bulk Ge lattice parameter through the formation of misfit dislocations at the interface, but these have threading arms which can penetrate the full thickness of the membrane unless steps are taken to encourage their annihilation. We have used a two-temperature growth method [6] by RP-CVD using an ASM Epsilon 2000 system with germane precursor. A thin initial low-temperature deposition of Ge absorbs most of

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the lattice mismatch and a subsequent thicker (~1 μm) layer grown at higher temperature produces low-defect relaxed material.

Two methods of producing Ge membranes from this starting material have been developed [8]. Fig. 1 shows the process of making suspended Ge structures by under-etching the patterned Ge layer with an anisotropic TMAH etch. Structures such as the spider web shown in Fig. 2 have been produced, which could be used for thermal isolation of a cooled bolometer [14].

In a second approach [15], Ge layers were grown on either side of a double-side polished, thin Si substrate. The "top" side Ge is deposited at high temperature and has slight tensile strain (although the Ge lattice is fully relaxed at the growth temperature, it becomes tensile strained on cooling due to the greater thermal expansion coefficient of the thin Ge epilayer than the thick Si substrate). The "bottom" side, compressively strained Ge is grown at a lower temperature. The wafer is then etched using TMAH from either the top or bottom face to produce a membrane. When tensile strain is used an extremely smooth surface roughness is measured AFM of ~2 nm (Fig. 3). These tensile strained Ge membranes can be produced with thicknesses from 60 nm up to 700 nm and areas up to 4 mm^2 [16].

3. Strain distribution

The tension in our Ge membranes and suspended structures has been measured using high-resolution X-ray diffraction (HR-XRD) at the DIAMOND Light Source. By using a compound refractive lens the intense X-ray beam from the synchrotron can be focussed onto the sample in a 3–5 μm diameter spot which means HR-XRD measurements can be made with high lateral resolution and in a far shorter time than would be possible using lab-based diffraction equipment [17]. The sample is mounted on an XYZ stage in a five circle diffractometer to enable strain measurements across the membrane, from reciprocal space maps (RSMs) taken every 10 μm along the $[1\bar{1}0]$ direction (Fig. 4a). With the Si(004) peak used as a reference throughout, the $q_{||}$ component of the Ge(004) peak position remains the same across the membrane and on the supported material surrounding, apart from a small discontinuity within ~30 μm of the edges. This confirms that, apart from at its edges, the membrane itself is free from tilt and flat relative to the original Si wafer. The FWHM of the Bragg peaks can be seen to be less for the suspended section of the membrane than on the Si support. This can be interpreted as confirmation that the misfit dislocation network has been removed from the suspended membrane, and so is not producing additional X-ray scattering for the central portion.

Fig. 4b shows how the tilt and in-plane strain varies across the membrane. There is partial strain relaxation at the membrane edge leading to bending of the lattice planes. The strain profile is symmetrical across the middle of the membrane and the membrane is slightly more tensile strained than the supported Ge. The $[0\bar{1}0]$ line profiles show identical behaviour to these along $[1\bar{1}0]$, demonstrating uniformity across the membrane.

A micro-Raman line scan across the membrane was measured as a comparison with the X-ray micro-diffraction. The Raman spectra were measured at room temperature with a high resolution HORIBA Jobin-Yvon spectrometer, using the 488 nm line of a mixed Ar:Kr laser in conjunction with a 50× objective. The focus diameter was approximately 1.2 μm. The Raman spectra were fitted using Lorentzian functions with a spectral accuracy of 0.03 cm^{-1}.

A micro-Raman line scan across the middle of the membrane was performed in a similar manner to the scanning X-ray micro-diffraction. Raman spectra were measured every 10 μm and the peak position of the Ge–Ge optical phonon tracked (Fig. 5). The

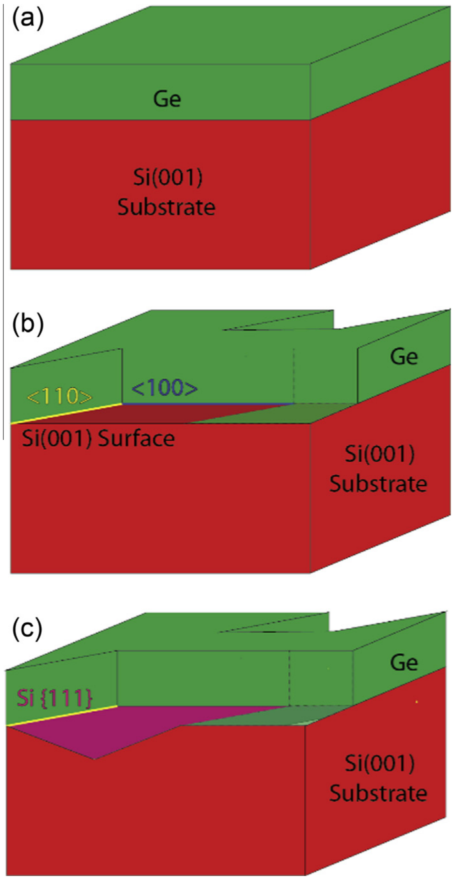

Fig. 1. Fabrication of under-etched Ge membrane: (a) the Ge-on-Si layer prior to patterning, (b) the structure after lithography and dry etching and (c) the suspended structure after anisotropic under-etching.

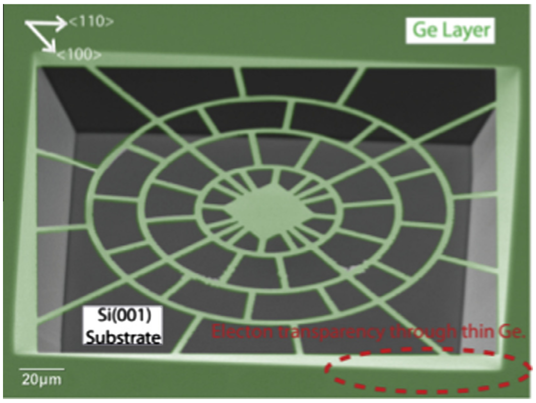

Fig. 2. SEM of etched, suspended Ge spider web; pale green areas are partially electron transparent in the thinned regions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

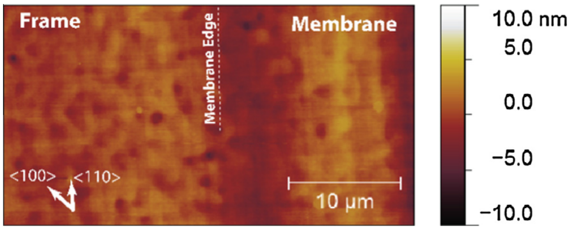

Fig. 3. AFM scan of a Ge membrane with RMS roughness of 2 nm.