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Near-Field Raman Microscopy of Si and Si-Based Structures Using AFM-Tip-Induced Breaking of Selection Rules

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1. Introduction

With miniaturization of semiconductor devices, mechanical stress influences increasing effect on device performances. Miniaturization of the device itself causes stress, in general. In particular, the use of shallow trench isolation and silicon-on-insulator structures results in stress in the transistor area. Obviously, stress plays an essential role in the strained Si devices.

This situation makes it necessary to precisely measure and control the mechanical stress in Si-based devices with high spatial resolution. Raman spectroscopy is a powerful tool for the stress measurement but the resolution of the method has diffraction limit of the order of the correspondent wavelength of the light. Near-field Raman spectroscopy can overcome this difficulty. Recently, it was shown that the local electric field near the apex of the metal AFM tip can be strongly enhanced giving advantage to the apertureless near-field microscopy and spectroscopy [1]. Raman spectra of the molecules and small particles placed near the AFM tip apex were actually obtained [2]. However, application of this effect to bulk materials is still the problem to be solved. In order to obtain Raman spectra with high spatial resolution, one needs to enhance near-field Raman signal and to suppress far-field Raman signal. In the present work, we propose a method that allows us to suppress the far-field signal thereby obtaining reasonable near-field signal for the first-order Raman band of Si.

2. Experimental

We used a near-field Raman setup based on the Renishaw micro-Raman spectrometer and the Nanonics AFM/SNOM system. This setup allows us to study Raman spectra in the back-scattering geometry. We used a super long working distance (15 mm) micro-objective lens (x50) for focusing and collection of the light, enebaling an AFM tip being introduced to the focused laser beam at the same side as (Fig. 1). This geometry is suitable for non-transparent samples like Si. An important thing is that we used a polarization configuration forbidden for the first-order Raman band of Si at 520 cm^{-1}. Both incident and scattered light were polarized parallel to the [100] axis of Si suppressing far-field Raman signal corresponding to this band.

AFM tips used were bent cone-shaped with 50 – 100 nm diameter apex made of silica glass coated with silver. Usually, the tip was oriented at 60 – 80 degrees to the Si wafer plane and the tip's projection to the Si wafer was oriented at ~ 45 degrees to the light polarization (i.e., parallel to Si [110] direction) (Fig.1).

A laser beam of 633 nm or 515 nm wavelength was focused by the micro-objective lens to ~ 3 μm spot. When the tip is introduced into the spot, near field for polarization parallel the tip projection (E//Z) is strongly enhanced [3] but there is practically no enhancement for the E⊥Z polarization. The tip-induced near field polarization is different from the far field polarization and one can obtain allowed polarization configuration for the near field when that for the far field is forbidden (tip-induced breaking of selection rules). Thus, the far-field signal can be suppressed while the near-field signal enhanced.

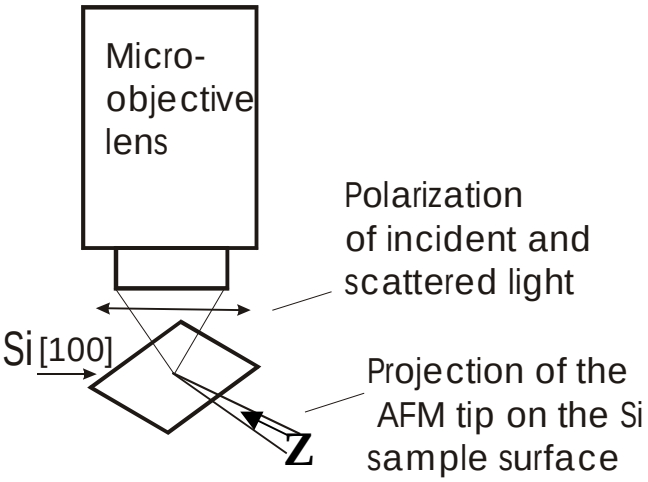

Fig. 1 Geometry of the experiment for observation of the near-field Raman signal of Si using tip-induced breaking of selection rules.

3. Results

We measured Raman spectra of Si for three cases under the above configuration: 1) without tip, 2) with tip in contact with Si surface and 3) with tip out of contact (distance between Si and tip ~ 500 nm). The results are shown in Fig. 2. Without tip, the first-order Raman band of Si at ~ 520 cm^{-1} is almost completely suppressed due to the forbidden polarization configuration. The intensity of this band is even lower than that of the second order Raman band of the acoustic phonon at ~ 300 cm^{-1}. With tip in contact, the intensity of the 520 cm^{-1} significantly increases. This is a strong evidence for influence of the tip on the polarization of the light. It is important to distinguish

between the near-field and far-field contribution to this effect. Near-field contribution can be removed when the sample is slightly retracted from the tip, other conditions being equal. The Raman spectrum labeled (with tip out of contact) corresponds exactly to this case. This spectrum shows intermediate (compared to other two spectra) intensity of the 520 cm^{-1} band. The near-field contribution to the band can be determined as a difference between the band intensities for tip in contact and tip out of contact.

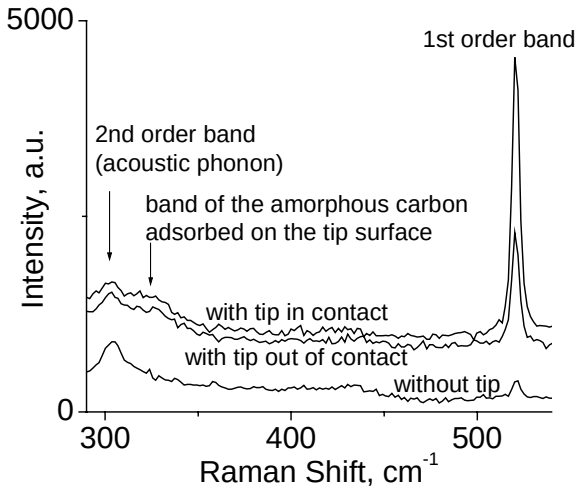

Fig. 2. Raman spectra of Si (forbidden polarization configuration) without tip, with tip in contact and with tip out of contact. The 633 nm line of the He-Ne laser was used for the excitation of the spectra, collection time being ~ 5 minutes.

Some luminescent background and additional Raman bands are observed in the spectra taken with tip, which are associated with the amorphous carbon adsorbed on the silver surface of the tip.

Thus, the above results verify that near-field first-order Raman signal of Si was actually obtained. Spatial resolution is determined by the size of the tip apex. In our case, it is in the range 50 – 100 nm. With sharper tips, it can be even better.

To demonstrate performance of our method, we actually measured Raman spectra of island structures fabricated in a strained Si layer formed on SiGe-on-insulator and achieved spatial resolution 100 – 200 nm. As shown in Fig. 3, the method enabled us to observe the Raman peak position varies as the distance from the island edge increases although in this measurement contribution of the far field Raman signal was quite strong.

3. Conclusions

In this work, we have proposed the method of obtaining high-resolution near-field Raman spectra of Si and Si-based structures using AFM-tip-induced breaking of selection rules. The method is experimentally demonstrated for Si wafer and is applied for real Si-based structures. The achieved spatial resolution is 100-200 nm at the moment but it can be significantly improved (to the range of ~ 10 nm) if the tip material and shape will be optimized.

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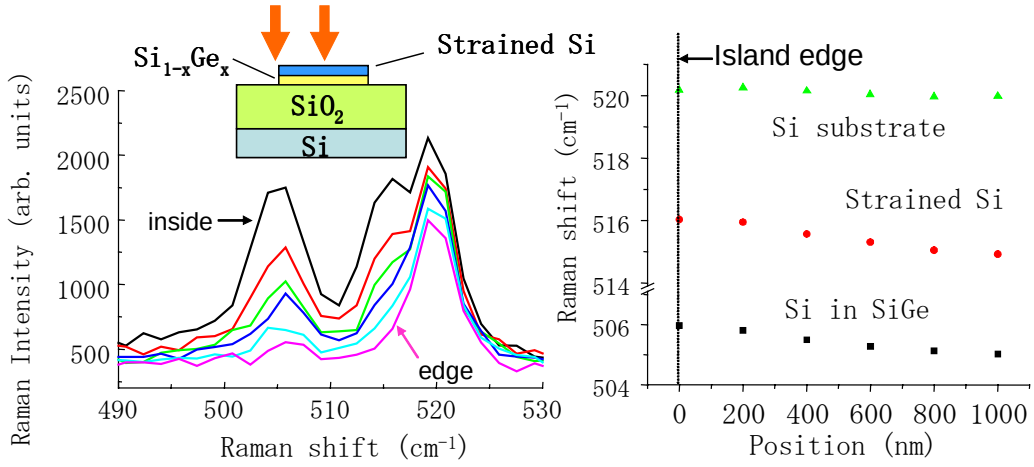

Fig. 3. Raman spectra for several points of Si/Ge structure with strained Si taken in forbidden polarization configuration with Ag-coated AFM tip in tapping mode, the step between the points being 200 nm (left). Dependence of the Raman band frequencies on the distance from the island edge (right).