The complexity of stress distribution in individual ultrathin strained silicon nanowires

早澤紀彦、タルン・アルバラード、河田聡、ムタナビア・オサマ

近接場ナノフォトニクス研究チーム

Stress behavior in ultrathin strained silicon nanowires directly on oxide is studied using high resolution polarized Raman spectroscopy. The investigated nanowires have lateral dimensions of 30, 50 and 80nm and length of 1μm top-down fabricated by patterning and etching a 15nm thick silicon membrane under biaxial strain of 0.6% generated using ultrathin layer transfer. The concern over the contribution of Raman scattering at the <110> oriented-sidewalls is circumvented by properly selecting the incident polarization relative to the sidewalls of the nanowire thus enabling a precise analysis of stress profiles in individual nanowires. Against the prevalent belief that nanowires are uniaxially strained as a result of free surface-induced relaxation [1,2], we demonstrate that stress profiles in single nanowire are rather complex and nonuniform along different directions [3]. As a general trend, higher stress is observed at the center of the nanowire and found to decrease linearly as a function of the nanowire width. Using multiwavelength (355nm and 442nm), high-resolution Raman we found that the stress is sensitive to the nanowire thickness. Particularly, the residual stress in the top ~10 nm of the nanowire is nearly uniaxial and increases from the edge towards the center, which remains highly strained. In contrasts, the average stress measured over the whole nanowire thickness including the silicon-oxide interface, exhibits different profiles characterized by a plateau in the region ~200nm away from the edges. This complex redistribution of stress induced by nanoscale patterning has direct implications for electrical and mechanical properties of strained silicon nanowires and provides myriad opportunities to create entirely new nanoscale devices.

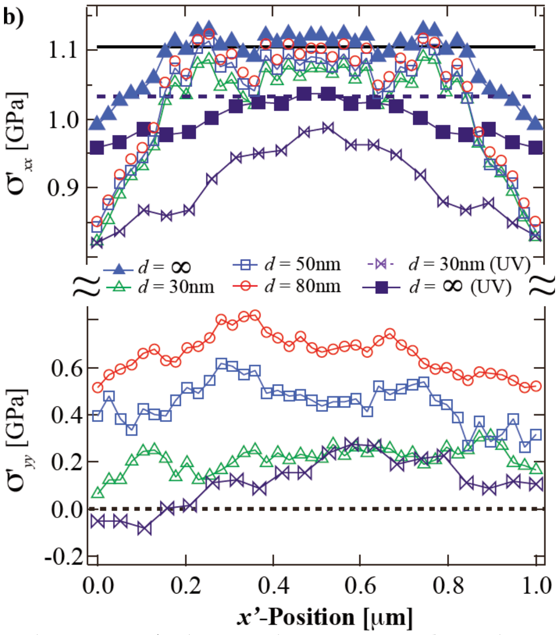

Figure 1 Anisotropic stress relaxation along nanowire

Figure 1 shows the obtained stress profiles $\sigma'_{xx}(x',d)$ and $\sigma'_{yy}(x',d)$ based on Jain's method [1]. The stress values along the *x'*-direction are below the original stress of the membrane. It is also interesting to note that the profile of the stress along *x*'-direction of the nanowires is similar to that of the edge sample (d= ∞). On the other hand, we can clearly see from the stress along the width, $\sigma'_{yy}(x',d)$, that the nanowire is still under biaxial. Only at the edge of the nanowire with *d* = 30 nm shows fully relaxed stress and become nearly uniaxial at the center having a 200 MPa stress. This behavior is observed for both excitation wavelengths. For *d*=80 nm and *d*=50 nm, the stress is well above the fully relaxed region (gray dashed zero line). This result indicates that the overall average stress in the nanowire is anisotropically biaxial. Hence, it is likely to obtain a nearly but not completely uniaxial average stress from an initially biaxial membrane through patterning. This is probably because with 442 nm excitation, the buried strained-Si/SiO_2 interface is probed and that the observed overall average stress is not completely uniaxial stress ($\sigma'_{yy} = 0$). For 442nm, the stress between $200 \leq x' \leq 800$ nm is comparable to the initial stress obtained from the membrane whereas for 355nm, only at regions between $450 \leq x' \leq 550$ nm shows similar stress with the strained membrane. Figure 2 exhibits the relaxation ratioat the center of the nanowire as a function of nanowire diameter. The extent of this relaxation along the width exhibits a linear behavior as a function of the nanowire width. : $\Delta\sigma'_{yy}/\sigma_0 = 1.01 - 5.77\ 10^{-3} \times d$. The relaxation along the long-axis is small and remains unchanged with the nanowire width.

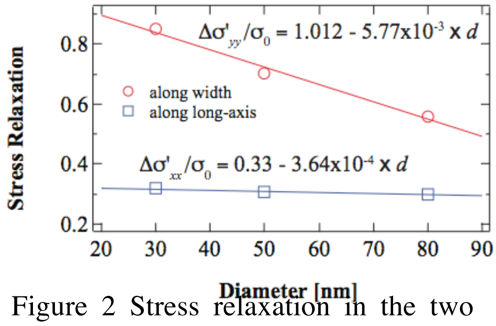

Figure 2 Stress relaxation in the two orthogonal directions.

The combination of two excitation wavelengths provides new insights into the complex behavior of stress in nanowires. Figure 3 shows the depth dependence of stress profiles along the two in-plane axes for nanowire with a width of d =30 nm under $z(x'x')z$ condition at different excitation wavelength (penetration depth) namely: 442 nm (~168 nm) and 355 nm (~10 nm). an interesting observation is that the stress relaxation behavior as obtained by the 355 nm excitation monotonously decreases towards the center of the nanowire which remains highly strained. Using the 442 nm excitation, the stress relaxation plateaus at regions between $200 \leq x \leq 850nm$. This dissimilarity in stress profile between the two excitation wavelengths is indicative of the nonuniform distribution of the in-plane stress along the nanowire thickness. For the two in-plane axes, the obtained stress profiles are qualitatively identical but remarkably different from the profiles measured for the top 10 nm or over the whole nanowire thickness. Particularly, the part of the nanowire near the interface becomes under a higher stress especially in the region about 100 to 200 nm away from the edge. In this region, close stress values are recorded for the two in-plane directions indicating that the interface with the oxide preserves almost the initial isotropy. Interestingly, the stress in x direction reaches values that are higher than the initial stress suggesting that the contraction of the lattice near the newly formed surfaces is accompanied by a strong distortion close to the interface with the oxide.

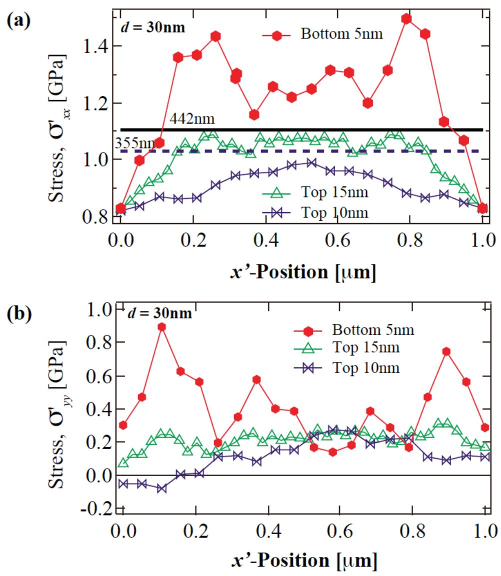

Figure 3 Complex stress relaxation in the depth direction.

[1] S. C. Jain, et al, Phys. Rev. B 52, 6247 (1995).
[2] F. Ma, et al, Appl. Phys. Lett. 98, 191907 (2011).
[3] A. Tarun, et al, submitted.