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Applied Physics Letters 2011, 99(24): 241906

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The following article appeared in Appl. Phys. Lett. 99, 241906 (2011) and may be found at <http://dx.doi.org/10.1063/1.3669413>

Date deposited: 6th October 2014

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Citation: [Applied Physics Letters](#) **99**, 241906 (2011); doi: 10.1063/1.3669413

View online: <http://dx.doi.org/10.1063/1.3669413>

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Experimental observations of surface roughness in uniaxially loaded strained Si microelectromechanical systems-based structures

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(Received 16 August 2011; accepted 21 November 2011; published online 14 December 2011)

Surface roughness in uniaxially loaded strained Si has been studied experimentally using high-resolution atomic force microscopy and a microelectromechanical systems-based on-chip loading device. A reduction in rms roughness from 0.29 nm to 0.07 nm has been identified as strain increases from 0 to 2.8% (stress from 0 to 4.9 GPa). The correlation length of the roughness, also known to affect carrier mobility, increases with increasing strain up to 1.7% before reducing at larger levels of strain. These results partly explain the high-field mobility observed in strained Si, indicating that a modified correlation length should also be considered in transport modelling of strained Si. © 2011 American Institute of Physics. [doi:10.1063/1.3669413]

The use of strained channels into metal-oxide-semiconductor field-effect transistors (MOSFETs) has proved to be one of the most promising choices to improve the performance of devices owing to the mobility enhancement for holes and electrons when compared with conventional unstrained Si channels.¹ Several reports in literature have experimentally demonstrated the improved performance of strained Si on several device architectures.^{2–4} Industry has adopted uniaxial loading technology due to the difficulties associated with producing biaxial strain states.⁵

While strain-induced performance enhancements at low electric field operation are well understood,⁶ the performance enhancement mechanisms in strained Si devices under high electric fields are still an open issue. Theoretical work suggests that reduced roughness scattering at high electric field regimes may result from the smoother surface of strained Si.⁶ Nevertheless, direct experimental evidence is still needed,⁷ particularly for devices deformed under uniaxial tension or compression where physical characterization of the surface is more challenging.

Surface morphology parameters such as rms height (Δ) and correlation length (Λ) are key to model the effect of the nanoscale roughness on carrier mobility at high electric fields. Simulations indicate that a reduction in Δ can increase electron mobility; however, the effect of Λ is less clear since mobility appears to increase at both low and high Λ values.⁸

Two recent works have reported an experimental correlation between surface roughness parameters and the device performance of biaxially strained Si MOSFETs. Bonno *et al.* confirmed, using high resolution atomic force microscopy (AFM) measurements, that Δ and Λ decrease under deformation,⁹ but only one level of strain was studied (0.8%). A sim-

ilar reduction of the roughness indices in deformed Si layers was found by Zhao *et al.*,¹⁰ using high resolution transmission electron microscopy (TEM). The range of strain was between 0.4 and 1.6%. Both works showed a large variation of mobility results from varying the strain, indicating that other material properties play a significant role in determining transport properties.

To date, surface roughness studies have only been carried out on biaxially strained material. The material characterization in devices deformed under uniaxial tension is challenging since strain is introduced during device fabrication, therefore, it cannot be investigated independently. As a result, device modeling of uniaxially loaded devices has been limited to the use of roughness parameters extracted from bulk Si and biaxially deformed layers,^{11,12} which could lead to erroneous or incomplete conclusions.

This work uses a microelectromechanical systems (MEMS) concept to deform released silicon beams in order to analyze the relationship between on-chip applied uniaxial stress and nanoscale surface roughness in Si. In addition to imposing pure uniaxial tension, this testing principle allows both high throughputs and high levels of deformation. Roughness parameters measured over a wide range of strain levels are reported in uniaxially loaded strained Si.

Figure 1 shows a schematic diagram of the MEMS-based loading stages used in this work. The test structures consist of a Si beam in which deformation is induced by the pulling action of a silicon nitride actuator (or “tensor”) involving large residual stress (resulting from high temperature deposition) and relaxing when released from the substrate (see Refs. 13–16 for details about the test concept and design and Ref. 17 for details on the fabrication specific to single crystal Si beams). The strain in the beam is determined by measuring the displacement u of the Si beam/actuator contact region with respect to its original position.

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FIG. 1. (Color online) Schematic of the MEMS-based uniaxial tension loading microstructure.

Embedded cursors are positioned on the beams and sidewalls for accurate determination of u . The mechanical strain ε is calculated as follows:

$$\varepsilon = \frac{u}{L_0} - \varepsilon_{mis}, \quad (1)$$

where L_0 is the initial length of the actuator and ε_{mis} is the possible initial mismatch in the Si layer.^{13,18} Raman spectroscopy was also used to provide an independent measurement of the strain in the Si beams, to complement the direct displacement measurements.¹⁹ The strain ranges from 0.2% to 2.8%, and it is obtained by varying the ratio of the silicon and silicon nitride beam lengths.¹⁴

AFM characterization is carried out using an XE-150 tool from Park Systems. Areas of $750 \times 750 \text{ nm}^2$ are scanned with a resolution of 2048 pixels per line, which results in a step of $3.7 \text{ \AA}$ between consecutive data points (Figure 2). All measurements are performed in non-contact mode using an ultra-sharp Si tip. This setup ensures large area coverage while maintaining a high scan resolution to allow the detailed study of specific regions. Noise conditions are minimised in an acoustic isolation chamber, and a simple median filter is also applied to the image to suppress any noise contributions. The noise floor of these measurements is $\sim 0.02 \text{ nm}$.

The lateral resolution of the measurements was verified by close inspection of small surface features such as surface pits and confirmed that the AFM tip is able to resolve features down to tip radius specification of 2 nm . However, since surface features smaller than 2 nm cannot be resolved, their contribution is not accounted for in the results presented in this work.

For each image, Λ is determined following the correlation analysis described in Refs. 9 and 20 assuming a Gaussian surface distribution for the correlation function. The Si surface may exhibit either an exponential^{9,19} or a Gaussian distribution.²¹ Both Gaussian and exponential autocorrelation functions can be used to extract comparable values of Λ

FIG. 2. (Color online) Selection of $95 \times 95 \text{ nm}^2$ regions from the $750 \times 750 \text{ nm}^2$ AFM scans.

(often with a variation $< 25\%$). However, most accurate results are achieved by employing the distribution that best fits the experimental data. Although some previous works used an exponential distribution to extract Λ ,^{9,19} data presented in this work were calculated using a Gaussian distribution since it provided the best fit to the experiment.

Figure 3 shows the quantification of Δ and Λ on deformed Si beams as a function of the strain. Increasing the strain from 0.2% to 2.8% clearly results in Δ decreasing from 0.34 nm to 0.2 nm . In contrast, the evolution of Λ with strain is less clear: for strain between 0.2% and 1.7%, Λ remains relatively constant with values around 5 nm ; however, there appears to be a large increase for strain levels above 1.7%. Although it is possible that significant topography modifications are only initiated at large deformations, more detailed analysis in specific regions of the surface can help to eliminate any contributions of long scale undulations. Therefore, nanoscale analysis is necessary in order to bypass the long scale undulations and concentrate on smaller surface features.

Nanoscale analysis is carried out on $95 \times 95 \text{ nm}^2$ areas selected from the original images as shown in Figure 2. Additional flattening is performed on each sub-image in order to minimize the contribution of long scale correlation length components and allow a more accurate extraction of the roughness parameters at the nanoscale. The resolution of each $95 \times 95 \text{ nm}^2$ sub-image is 256 pixels per line, the same resolution as that used in conventional AFM scans.

The quantification of roughness parameters at the nanoscale is shown in Figure 4 as a function of strain. The data show that Δ continues to decrease as strain increases, similar to the trend shown in Figure 3(a). However, nanoscale values for Δ at high levels of strain reduce below 0.1 nm , which is a reduction of more than 50% compared with the values shown in Figure 3(a). This confirms that long scale undulations make a significant contribution to roughness, which is also reflected in the extraction of Λ . In contrast with Δ , Λ exhibits a different trend with increasing strain; high levels of strain result in Λ reducing to almost 4 nm (Figure 4(b)). These measurements of uniaxial stress-induced roughness in Si agree with previous observations of decreasing Λ for increasing biaxial strain.^{9,10}

It may appear counterintuitive that large levels of tensile strain could induce a reduction in the average distance between nanoscale surface undulations instead of an

FIG. 3. Variation of surface roughness parameters with strain in the Si beam measured on $750 \times 750 \text{ nm}^2$ AFM images: (a) rms roughness Δ and (b) correlation length Λ .

FIG. 4. Variation of surface roughness parameters with strain in the Si beam measured on $95 \times 95 \text{ nm}^2$ AFM images: (a) rms roughness Δ and (b) correlation length Λ . The error bars indicate the maximum variation in the calculation (error bars for Λ are smaller than the symbols).

“elongation” of the surface features resulting from stretching the Si beam. However, it has been suggested that high stress can modify the surface energy of the semiconductor, which may lead to mass migration as the mechanism affecting the surface roughness.^{22,23} Therefore, it is likely that the surface morphology of the highly loaded samples exhibits shallower undulations but in closer proximity to each other compared with those in low strain or unstrained samples, as observed.

The impact of processing on the surface roughness of the test structures was monitored by comparing the unprocessed SOI material with SOI regions in the sample following processing, in unstrained regions. As highlighted in Figure 4, the surface of the unprocessed SOI sample was found smoother than the processed material. Both Δ and Λ are higher in the processed SOI sample compared with unprocessed SOI material. Nevertheless, since fabrication of all the beams is simultaneous, the process induced roughening impacts all Si beams equally, and the trends and changes reported are not affected. Further, the surface roughening in the processed microstructure samples is likely to originate during the formation of the thermal oxide. This is common during MOSFET gate processing and may impact device interface roughness and should be considered in studies of surface roughness.²⁴

In conclusion, the impact of uniaxial tension on the evolution of nanoscale surface roughness in Si has been investigated. Uniaxial tension is induced in Si beams through the relaxation of the residual stress of a long silicon nitride actuator attached to the beam, producing strain levels between 0.2% and 2.8%. The rms roughness was found to reduce gradually from 0.29 nm for unstrained Si to 0.07 nm for 2.8% strain. Nanoscale characterisation shows that the correlation length is also affected by increasing strain. The correlation length of the surface undulations in the direction of

the applied stress reduced from 5.3 to 4.3 nm for strain increasing to 2.8%. These results partly explain the high-field mobility observed in strained Si and indicate that a modified correlation length should be considered in transport modelling of strained Si.

This work has been carried out under the EU FP7 NANOSIL framework and the European commission and the Walloon region supporting the research project MINATIS.

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