AIP | Applied Physics Letters

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Citation: Appl. Phys. Lett. 96, 113508 (2010); doi: 10.1063/1.3358149
View online: http://dx.doi.org/10.1063/1.3358149
View Table of Contents: http://apl.aip.org/resource/1/APPLAB/v96/i11
Published by the American Institute of Physics.

Strain evolution during the silicidation of nanometer-scale SiGe semiconductor devices studied by dark field electron holography

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(Received 29 December 2009; accepted 15 February 2010; published online 16 March 2010)

SiGe is routinely used to induce strain in modern semiconductors in order to improve the mobility of the carriers in the channel. Due to the absence of a technique that can accurately measure the strain in these devices with nanometer-scale resolution it has been difficult to assess the effects of processing such as silicidation on the compressive strain in the conduction channel. Here we show that by using dark field electron holography, the strain evolution at various stages of the device processing can be observed, showing that the silicidation process does in fact significantly reduce the strain in the conduction channel. © *2010 American Institute of Physics*.
[doi:10.1063/1.3358149]

Strain is routinely used in modern semiconductor devices in order to increase transport properties.[1] This is achieved by etching the source and drain regions on each side of the transistors and then filling the recesses with either higher or lower lattice parameter materials in order to induce uniaxial compressive or tensile strain in the Si channel. This has the effect of increasing the mobility of the holes or electrons in the conduction channel. Whereas the electrical impact of strain on transport is rather well understood, there are few results on the two-dimensional (2D) distribution of strain at the nanometer scale in the channel, mainly due to an absence of a suitable experimental technique.

Here, a transmission electron microscope (TEM) based technique called dark field holography[2] has been used to provide strain maps for 30 to 40 nm gate length test structures with SiO_2/Si_3N_4 dummy gates and recessed SiGe sources and drains with Ge contents of 23% and 35%. Wafers were also grown with a 9-nm-thick layer of nickel deposited onto surfaces which is used to form the electrical contacts on SiGe devices using a process called silicidation.[3] The source and drain components are contacted by forming a monophase NiSi region for low resistance electrical contacts. To achieve this monophase NiSi an anneal temperature of 450 °C is needed.[4] It is not known how this process affects the strain in these SiGe devices, principally because up until recently there was no suitable technique that could be used to measure strain in these devices with nanometer-scale resolution.[5]

Dark field electron holography is an new technique that was originally developed by Hytch and co-workers at CEMES in Toulouse.[2,6] Dark field holography uses almost the same procedure as has been used for the mapping of dopants or magnetic fields.[7] In classical off-axis holography, an electron biprism is used to interfere a electron beam passing through the region of interest, Ψ_{obj} with a beam that passes through only vacuum Ψ_{ref}. For dark holography, Ψ_{obj} is restricted to a given diffracted beam, g which is brought to the optical axis of the microscope and selected by the objective aperture. The strain can then be determined by passing Ψ_{ref} though a reference perfect crystal, which in this case is a silicon substrate. Dark holography is extremely well suited for the characterization of strained semiconductor devices as 2D strain maps with a nanometer-scale resolution, a large field of view and excellent sensitivity can be obtained from a single electron hologram. By comparing the maps obtained from simple test structures with simulations it has been shown that dark field electron holography can be used to accurately measure the strain with a precision of 0.02%.[8] However, in order to provide an accurate measurement of the strain for the devices the relaxation of the thin TEM specimens must be taken into account.[9]

SiGe devices with Ge concentrations of 23% and 35% were examined both with and without the Ni deposition and then after each anneal stage. Specimens were prepared by *in situ* lift out using a FEI Strata 400 focused ion beam system operated at 30 kV. A layer of protective resin was applied to the top of the specimens so that a layer of protective tungsten could be applied to the specimen without changing the strain in the specimens. The resin was then removed using a plasma cleaner. A final milling stage was performed at 8 kV to reduce the surface damage. Although TEM specimens can be cleaned using lower energies we found this to be a compromise between reducing the surface damage and maintaining the parallel sides of the specimen that are required for electron holography. All of the different TEM specimens examined had thicknesses of between 140 and 160 nm which were measured using convergent beam electron diffraction.

Electron holograms of the specimens were acquired using an FEI Titan TEM. The specimens were examined in dark field mode with the {220} diffraction spots selected in order to provide strain maps showing the compressive strain in the conduction channels. It was also possible to acquire dark holograms for the {004} reflection to provide strain maps in the growth direction. These maps are not shown here, however as expected, no strain was measured in the conduction channel for the {004} direction. The exceptional mechanical and electrical stability of the Titan allowed electron holograms with a fringe spacing of 2 nm to be recorded for 64 s leading to excellent signal to noise in the reconstructed phase images.[10] The long acquisition times are especially relevant for dark field electron holography where the

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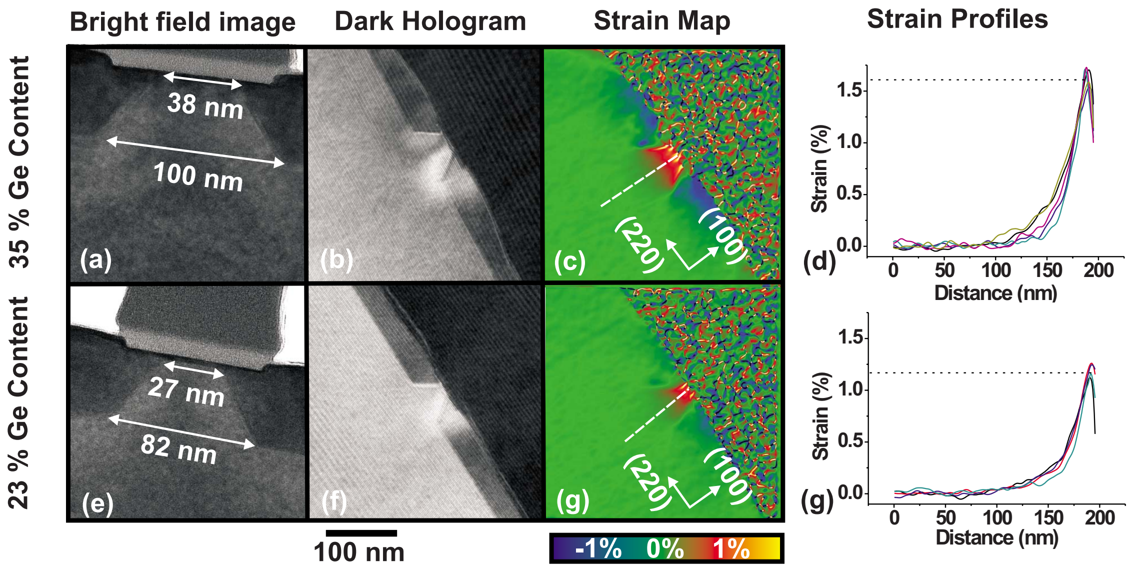

FIG. 1. (Color online) shows (a) a bright-field TEM image, (b) a dark field electron hologram for the {220} diffraction spot, (c) a strain map for the {220} direction and (d) profiles extracted from the indicated region in the strain map for a SiGe device with a Ge content of 35%. (e), (f), (g), and (h) are as above except for a SiGe specimen with a Ge content of 23%.

intensity in the recorded images can be very low. The holograms were converted into strain maps with a spatial resolution of 6 nm using software developed at CEA. In order to perform dark field electron holography it is necessary to tilt the specimen into a two-beam condition which can have the effect of spreading the measured strain near the interfaces. By examining thin TEM specimens this effect can be minimized, however care was taken to ensure that the specimen was tilted by as small amount as possible during each experiment.

Figure 1 shows the results obtained by dark holography before the Ni deposition on the specimens. Figure 1(a) shows a bright-field image of a 35-nm-gate device with the dimensions clearly indicated. The gate width of this specimen measured is 38 nm. Figures 1(b) and 1(c) show a dark field electron hologram containing the region of interest and a map showing the strain measured in the {220} direction, respectively. The profiles have been extracted from the strain map and are shown in Fig. 1(d). The profiles are extracted from the region indicated by the dashed line in the strain map and have been averaged across only 3 nm which is less than the spatial resolution. These strain profiles are shown exactly as measured, no flattening or normalization procedures have been applied. Here positive values of strain indicate compression. Six strain profiles are shown and these were acquired from different devices at different times and a spread in the strain measurement of around $\pm 0.1\%$ can be seen. This variation is higher than the previously demonstrated sensitivity of the technique and may be due to combinations of differences in the value of strain in the actual specimens as well as due to experimental error arising from specimen relaxation and small differences in thickness in the different TEM specimens as well as experimental noise. The measured strain in the devices with the 35% Ge concentration is $1.6 \pm 0.1\%$. In Fig. 1 the presence of narrow high strain streaks of up to 5 nm in length can be observed directly under the gate. At this time it is not known if these are artifacts or real and for this study the strain profiles were measured away from these high strain regions.

Figures 1(e)–1(g) show a bright-field TEM image of a SiGe device with a Ge content of 23%, a dark field electron hologram for the {220} reflection and a strain map in the {220} direction, respectively. The bright field image shows that the gate length for this specimen is only 27 nm. Profiles extracted from across the region indicated by the dashed line in the strain map are shown in Fig. 1(h). The strain measured in the channel is $1.2 \pm 0.1\%$, which is less than observed for the other specimen with the Ge content of 35% and the larger gate width.

The specimens with the 35% and 23% Ge content were examined at various stages during the silicidation process using dark holography. Figure 2 shows bright field images, strain maps, and profiles during the processing for the speci-

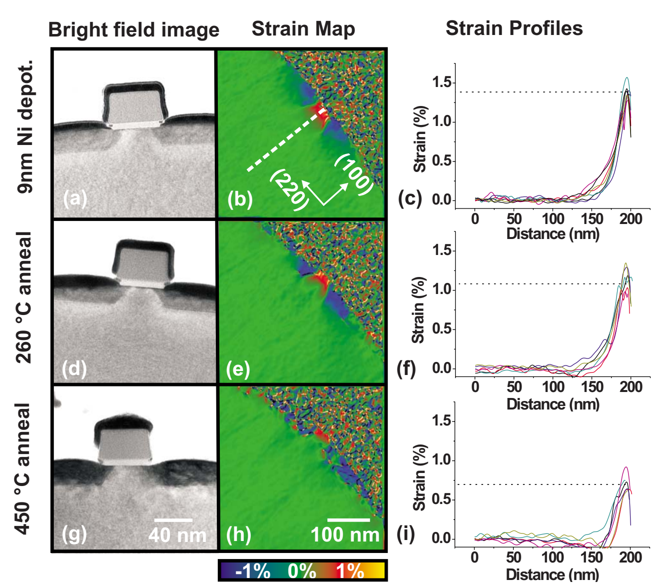

FIG. 2. (Color online) (a), (b), and (c) show a bright-field TEM image, a {220} strain map, and profiles extracted from the region indicated by the dashed line in (b) for the SiGe device with a Ge content of 35%. (d), (e), and (f) are as above except after a 260 °C anneal. (g), (h), and (i) correspond to the specimen after a 450 °C anneal.

TABLE I. Table showing the strain measured directly under the conduction channel for the SiGe devices with different Ge contents after different stages during the silicidation process. In all cases the experimental error is estimated to be ±0.1%.

Stage	35% Ge Content	23% Ge Content
Before silicidation	1.6	1.2
After silicidation	1.4	1.1
After 260 °C anneal	1.1	1.1
After 450 °C anneal	0.7	0.4

mens with the 35% Ge content. Figures 2(a)–2(c) show the results after deposition of a 9 nm layer of Ni onto the specimens. The presence of the Ni can be clearly seen in the bright field image. Here a strain of 1.4 ± 0.1% is measured showing that just the deposition of Ni onto the specimen surface has modified the strain. Figures 2(d)–2(f) show the results from the specimens after an anneal of 260 °C. The TEM image shows that the Ni and the Si have begun to react together and the strain maps suggest that there is a reduction in the compression in the channel to 1.1 ± 0.1% after this intermediate annealing stage. It is known that an anneal of 450 °C is required in order to form the monophase NiSi and Figs. 2(e)–2(g) show the results after this annealing stage. Here it is clear from the TEM image that the SiGe region has been completely reacted with the Ni which should certainly affect the values of compression observed in the devices. Indeed, the strain after this 450 °C anneal is now 0.7%, which is a reduction of more than a factor of 2 from the original value. Six experimental profiles are shown at each stage of the experiment giving an indication of the reproducibility of the technique. Again, the spread of the results is ±0.1%, and within this experimental error, the measured strain seems extremely reproducible. These experimental results have also been successfully reproduced in repeat measurements on additional specimens that were prepared from different parts of the wafer. From these results it is clear that the silicidation process has a significant influence on the strain that is present in the channel of these nanometer-scale SiGe devices with the 35% Ge content.

Table I shows the maximum value of compressive strain in the {220} direction that have been measured directly under the gates for both the specimens with the 35% and 23% Ge contents. The device with the 23% Ge content was also examined during the silicidation process, here the strain was only reduced from 1.2% to 1.1% during the silicidation and first anneal stage, and then to only 0.4% after the 450 °C anneal.

It is clear that the silicidation process has a significant effect on the compressive strain measured in the channel. During processing it is necessary to anneal the wafers to 450 °C in order to provide the required monophase NiSi that is required for the electrical contacts, however, this processing step reduces the strain from 1.6% to 0.7 ± 0.1% for the devices with the 35% Ge content. For devices with a 23% Ge content the strain is reduced to only 0.4 ± 0.1% which is only one third of the original value.

Dark field electron holography as used here to characterize nanometer-scale devices, appears to give quite reproducible results albeit with a large spread of results (±0.1%) when compared to the demonstrated sensitivity of the technique on simple calibration samples (±0.02%). The 6 nm spatial resolution that has been demonstrated here for dark holography will be improved in the future with the new generation of electron sources with better coherence. In addition, better than 2 nm spatial resolution has been demonstrated (at the expense of the field of view) by the research group at IBM by using special lens settings.[11] From the point of view of device processing, there are many different approaches that need to be tried in order to preserve the strain in the channels during the silicidation process. With the use of characterization techniques such as dark holography we will be able to determine the best processing methods for the developments of the 22-nm-gate technologies and beyond.

This work has been performed within the IBM-ST Microelectronics-LETI alliance.

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