Anisotropic conductivity of silver thin films grown on silicon (100) vicinal surfaces

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The electrical conductivity between 4 and 300 K of Ag thin films (up to 30 nm grown at room temperature on Si(100) vicinal surfaces has been measured and their morphology imaged with an atomic force microscope. A noticeable anisotropy of the resistivity of the films which is related to the structure of the films has been found. © *1995 American Institute of Physics.*

Although electronic transport in thin metallic films grown on amorphous substrates has been investigated for many years; thin films grown on monocrystalline substrates have been so only recently. Probably the most extensive studies with monocrystalline materials concern $CoSi_2$ and $NiSi_2$ thin films grown on different faces of silicon.[1–3] Theses silicides are metallic and continuous for thicknesses of several monolayers. Some studies of Ag and Pb, which do not react with silicon, and which form abrupt interfaces have also been reported.[4,5]

Apart from very thin films for which some authors observe localization effects[6] and other claim to obtain evidence for quantum size effects,[5] the resistivity of metallic films grown on monocrystalline substrates has been found to be similar to that of a homogeneous and isotropic medium. In this letter we report on an anisotropic resistivity of Ag films grown on vicinal Si(100) 2×1 reconstructed surfaces and we point out potential applications of a preferential growth on these surfaces for fabricating one-dimensional conductors.

It has been shown that reconstructed 2×1 Si(100) surfaces are, in general, made of 2×1 and 1×2 randomly distributed domains, the Si-Si dimers which give rise to the 2×1 reconstruction are alternately along $[011]$ and $[0\bar{1}1]$ in consecutive atomic planes separated by steps.[7] Appropriate vicinal surfaces with the steps in the $[011]$ direction create double height steps and monodomain surfaces with the Si–Si dimers parallel to the step edges.[8,9] Vicinal surfaces and 2×1 reconstructed surfaces have a twofold symmetry which is at the origin of the anisotropies described in this letter.

The growth of Ag on Si(100) 2×1 has been investigated with various techniques including the scanning tunneling microscope.[10,11] These studies included that silver grows at room temperature in the Stranski–Krastanov mode as preferentially oriented elongated Ag islands.

For our experiments, the Si substrates were 0.3 mm thick phosphor doped n-type wafers with a resistivity $>0.50\ \Omega$ m and were prepared, as for previous photoemission and optical studies,[12] in an ultrahigh vacuum chamber by heating to 900 °C. The samples were grown on the (100) vicinal surfaces tilted 5° about the direction $[011]$. It has been shown that such surfaces are nearly monodomain.[9] LEED patterns of our (100) vicinal surfaces indicate the existence of a preferential domain. The splitting of the spots of the LEED pattern due to the steps are clearly observed. The edge of the steps is perpendicular to the direction given by the line joining the split spots and was marked for the subsequent resistance measurements. For nonvicinal surfaces neither preferential 2×1 domains nor splitting of the diffraction spots were observed.

Ag was deposited at a rate of about 0.005 nm (s^{-1}) on the substrate maintained at room temperature. In all cases, the resistance of the Ag films was at least 100 times smaller than that of the Si substrate.. Thicknesses were determined by a quartz oscillator calibrated by measuring the thicknesses of the samples by Rutherford backscattering.

For each film, a small square with sides parallel to the $[011]$ and $[0\bar{1}1]$ directions was cut from near the center of the wafer. Four Al wires attached by thermocompression or with silver paint were positioned in each corner for resistance measurements using the van der Pauw technique.[13] A computer controlled acquisition system comprising resistance bridge, temperature measurement, and switching system was used for the measurements. At first, only the two current directions were measured, but when it became apparent that the resistance was very different in the two directions, the other two symmetrical configurations were also measured to check for asymmetrical experimental artifacts and inhomogeneities. The resistance was found to be anisotropic in directions parallel to the sides of the square.

Figure 1 shows the resistance in the two perpendicular directions for a 18.7 nm thick film. The ratio of the two resistances is 32 at 4.2 K and decreases to 27 at room temperature. For an isotropic material, the curves in Fig. 1 should be superposed. In order to highlight the effect, resistance measurements on a 16 nm thick film grown on a nonvicinal surface have also been plotted. For this surface a 2×1 reconstruction was observed with an identical contribution of both domains. The electrical anisotropy is larger for the vicinal surface and is probably induced by its vicinal character. However, it is not clear whether the anisotropy is due to the existence of preferentially oriented domains or to steps regularly distributed on the vicinal surfaces. Although the van der Pauw configuration does not allow accurate values of the resistivity to be obtained for very large anisotropies, an indi-

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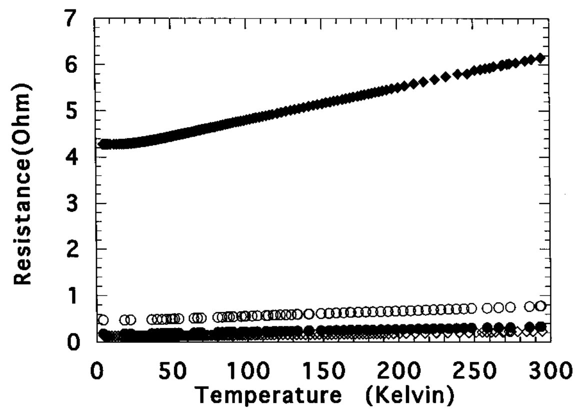

FIG. 1. Resistance of an 18.7 nm thick Ag film in the [011] direction, i.e., parallel to the steps (♦) and in the direction [01$\bar{1}$], i.e., perpendicular to the steps (◇), and 16 nm thick Ag film grown on a nonvicinal surface (○), (●).

cation of the resistivity in both directions was extracted from the resistance data using the method described by Montgomery.[14] Figure 2 shows the resistivity deduced by this method. The thickness of the films was assumed to be that measured by the quartz balance during deposition. Note that the resistivity ratios are 2.9 and 1.3 for the vicinal and nonvicinal surfaces, respectively. In the low resistance direction, the resistivity is considerably higher than that of silver even taking into account corrections for the thickness limited mean free path. This indicates that the film contains a high concentration of defects such as grain boundaries which limit the electron mean free path. A thicker film (30 nm) deposited on a vicinal surface showed a similar effect with a smaller ratio of the resistances of 4.6 and with a resistivity anisotropy at 4.2 K of 1.6.

A possible origin of the high resistivity and the anisotropy is apparent in Fig. 3 which shows an atomic force microscope image of the sample grown on a vicinal surface whose resistance is shown in Fig. 1.

This image was obtained with a commercial instrument (Topometrix Ltd.) which measures the force by the beam

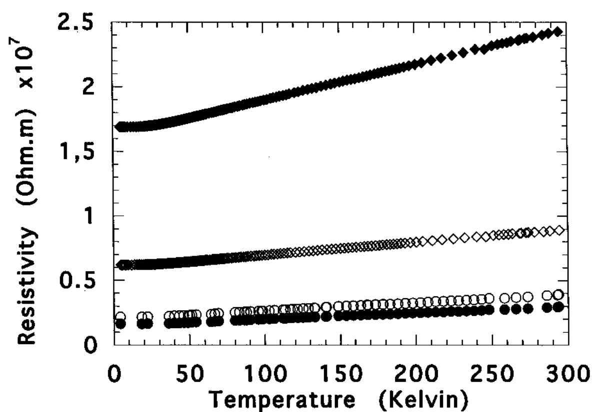

FIG. 2. Resistivity of an 18.7 nm thick Ag film in the [011] direction, i.e., parallel to the steps (♦) and in the direction [01$\bar{1}$], i.e., perpendicular to the steps (◇), and of a 16 nm thick Ag film grown on a nonvicinal surfaces (○), (●).

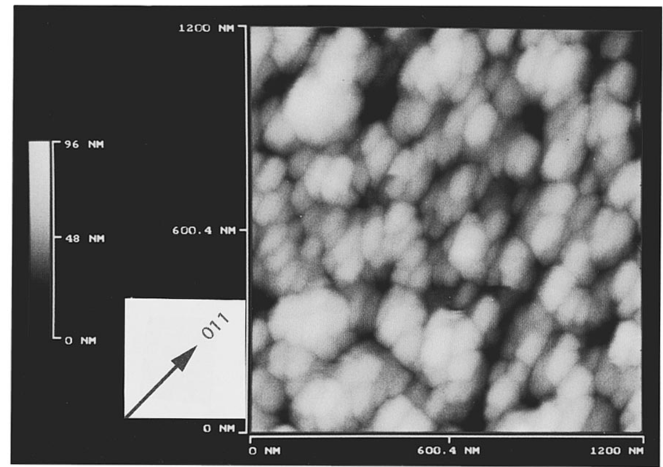

FIG. 3. Atomic force microscope image of the vicinal sample measured in Fig. 1.

deflection method. We used a microfabricated cantilever having a force constant of 0.06 Nm^{-1}. The silicon nitride tip integrated in the cantilever is a pyramid with a 4 μm square base. The most important property of the image is the observation of an anisotropic structure, which is confirmed by taking the Fourier transform of the image. Note that the images given by the microscope are rotated by 45°, so that the direction [011] is along the diagonal of the photograph (Fig. 3). The sample is made of grains elongated in this direction parallel to the steps and it should be noted that the film has a rather compact structure. The mean length of the grains is about 100 nm and their width about three times smaller. The direction of the anisotropy has been carefully compared and correlated with that of the resistance. We have verified that the anisotropy is representative of the sample by taking images at well-separated places on it. The symmetric shape of the pyramidal tip ensures that the anisotropy of the image is not due to it. As a further precaution we have taken images of a thin gold film vacuum deposited on mica. This showed no anisotropy at all. Moreover, no anisotropy was detected either by direct image inspection or by taking the Fourier transform of the image of the 16 nm film grown on the nonvicinal surface whose resistance is shown in Fig. 1.

The relatively high value of the resistivity indicates a connected path but with many structural defects. The formation of flat-topped islands with a trapezoidal cross section, elongated along the direction parallel to the steps was recently observed for Ag deposits on Si(100) 2×1 (Ref. 11). Figure 3 could correspond to connected islands with symmetric facets that avoid coalescence. Obviously the anisotropy of the structure and of the resistivity of the films originates in the anisotropy of the Si surface. For thicker (several tens of nanometers) Ag films, the anisotropy is smaller.

A puzzling fact is that the resistance is larger in the direction of the elongated islands. Experiments measuring the resistivity of Cu films on Si(100) 2×1, by the four point method showed an anisotropy and an abnormally low resistivity in the direction perpendicular to the steps whose origin is still unclear.[15]

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In conclusion, we have observed an appreciable anisotropy in the resistivity of Ag films grown at room temperature on vicinal Si(100) surfaces. This anisotropy has been shown to be correlated with a pronounced structural anisotropy observed by atomic force microscopy. With an appropriate choice of growth conditions (temperature, film thickness, etc). the resistance anisotropy could be made larger. Then, only thin films with metallic conduction in one direction could be made. Such films may have the potential for applications where highly anisotropic electrical conduction is required. However, more experimental effort is needed to understand the detailed mechanisms of the observed effect and additional experiments to this end are in progress.

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