# Switching Between One and Two Dimensions: Conductivity of Pb-Induced Chain Structures on Si(557)

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We show in a combined study of four-point conductance measurement and tunneling microscopy that surface state conductance induced by one monolayer of Pb on Si(557) can be quasi one dimensional with conductivity values close to typical three-dimensional metals. At a critical temperature of $T_c = 78$ K, associated with an order-disorder phase transition and a tenfold superperiodicity along the Pb chains, the system switches from low to high conductance anisotropy, with a semiconductor-insulator transition in the direction perpendicular to the chain structure, while along the chains conductance with a $(1/T + \text{const})$ temperature dependence was found.

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The electronic properties of low-dimensional systems are intimately related to their geometric structure. In ideal one- or two-dimensional systems the electron confinement is important, leading to an increased electron correlation [1] with strong deviations from the Fermi liquid and formation of a Luttinger liquid [2,3]. Particularly in one-dimensional systems the enhanced interaction is accompanied by instabilities. Interactions between lattice, charge, and spin cause formation of charge and spin density waves that lower the energy and lead to metal-insulator transitions in the electronic transport properties of such a system [1,4].

In general, one- or two-dimensional systems cannot be suspended in free space, and their realizations are always approximate using either strongly anisotropic crystals [5,6] and polymers [7], or supporting surfaces [8]. Especially adsorbed layers, which partly form chain structures on substrates like Si(111) [8,9], allow precise access to the relation between geometric and electronic properties of quasi-one-dimensional systems. A recent realization is the submonolayer adsorption of Ag and Au atoms on vicinal Si(111) surfaces [e.g., Si(557), Si(553)] [10–12]. It is in fact this coupling with the underlying substrate, i.e., the energetic, electronic, and relaxational interplay between the inevitable embedding substrate material and the adsorbate, that determines even the effective dimensionality of such systems.

A particularly intriguing example of this interplay is the system Pb/Si(557). The alternation of (111) and (112) oriented microfacets of the clean Si(557) sample seems to be unchanged by Pb adsorption (see below). On both facets the adsorption of Pb is known to modify only slightly the energetic position of occupied Si surface states at concentrations up to one monolayer (ML), which pin the Fermi level close to a midgap position [13]. Thus the underlying Si interface is always charge depleted irrespective of doping. Using an undoped Si sample we are thus able to measure almost pure surface state conductance even over macroscopic distances, as also corroborated by the measured Pb coverage dependence (see below).

In this Letter, we describe temperature dependent macroscopic dc conductivity measurements of just one ML of Pb obtained after high temperature annealing in order to desorb all multilayers and form a chain structure on this surface. As revealed by tunneling microscopy (STM), switching between conductance with high and low anisotropy, respectively, is coupled with an order-disorder phase transition. A remarkably high conductivity along the chains in the highly anisotropic state is found which decreases as a function of temperature between 4 and 80 K, excluding the occurrence of Peierls transitions, as observed in comparable systems [9], and even a dominant influence by defects on these results.

The experiments were carried out under ultrahigh vacuum conditions at base pressures lower than $5 \times 10^{-9}$ Pa in two separate vacuum chambers, set up for conductivity measurements at variable temperatures down to 4 K, and for tunneling microscopy at variable temperatures, respectively. In both chambers the average morphology was controlled by low energy electron diffraction (LEED), the cleanliness of the Si surfaces by STM and by Auger spectroscopy. The Si(557) substrates (Crystec, Berlin) were chemically cleaned *ex situ*. Atomically clean Si(557) surfaces were obtained after heating these substrates to 1370 K for 10 sec in vacuum, followed by annealing for 15 min at 1030 K and slow cooling to 600 K. Pb was evaporated from thermally heated $Al_2O_3$ crucibles. The Pb coverage was calibrated both by conductivity measurements of thick Pb films grown on Si(111) substrates at 20 K [14] within an accuracy of 5% of a ML, and by Auger spectroscopy monitoring the Pb (OVV) and (NOO) transitions during initial growth of Pb layers as a function of coverage (accuracy $\pm 0.1$ ML). An extended four-contact geometry was used [cf. with Fig. 1(d)] with eight predeposited macroscopic $TiSi_2$ contacts, approximately 50 nm thick, that are separated pairwise by slits machined into the samples as shown in Fig. 1. By automatic switching between equivalent sets of contacts, the conductivity was measured sequentially parallel and

 

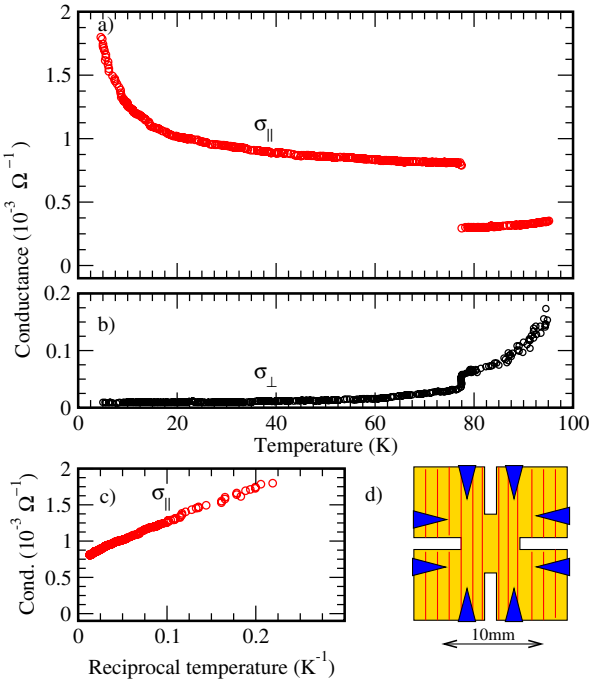


FIG. 1 (color online). Conductance of the Pb-wires, after high temperature treatment as described in the text, measured along the $[\bar{1}\,\bar{1}\,2]$ ($\sigma_\perp$, panel a) and the $[1\bar{1}0]$ directions ($\sigma_\parallel$). (c) $\sigma_\parallel$ below 78 K versus $1/T$. (d) Schematic drawing of the Si(557) samples with the arrangement of $TiSi_2$ contact pads. The lines indicate the stripe structure along the $[1\bar{1}0]$ direction.

perpendicular to the steps. The separation between equivalent contacts was approximately 10 mm. In all measurements contributions of the clean Si substrate (measured resistance 16 kΩ at room temperature, >500 kΩ below 150 K) were carefully subtracted. Pb layers up to 0.5 ML produced no measurable changes of resistance, as expected from the results of Ref. [13]. Using He evaporation cryostats, the samples were cooled down to 3.5 K in the conductivity apparatus (apparatus A), and to 40 K in the STM machine (apparatus B). The temperature was measured with calibrated silicon diodes, in apparatus A on the cryostat and with a thermally completely shielded sample, and in machine B directly on a dummy sample.

For Pb layers evaporated onto the Si(557) samples at low temperature (25 K) onset of measurable Pb-induced conductance was found close to 0.7 ML (ML given with respect to the density of Si surface atoms), which as a function of temperature, shows an activated behavior. The conductance in the direction parallel to the steps, $\sigma_\parallel$, was typically larger by only 30% to 50% than perpendicular to the steps, $\sigma_\perp$, at coverages above 1 ML. Up to coverages of 3 ML $\sigma$ contains both temperature activated and nonactivated contributions (as judged by the nonzero extrapolation to 0 K). The latter dominates already at a coverage of 2 ML, turning into purely metallic behavior at Pb coverages of 4 ML and more. It is characterized by weak anisotropy of an essentially two-dimensional Pb layer, and will be described in detail elsewhere [15]. Very similar behavior was found for Pb layers on flat Si(111) surfaces [14].

The strong anisotropy close to one-dimensional behavior, however, was induced by high temperature annealing to 640 K for several minutes. This annealing temperature was directly calibrated with a Ni-NiCr thermocouple on a dummy sample with an uncertainty of ±2 K. Using our Auger calibration of the Pb concentration, we determined the remaining coverage as 0.9 ± 0.1 ML with respect to the atomic surface concentration of the Si(557) surface. The assumption of close-to-monolayer coverage is fully compatible with the STM results described below.

An example of the measured conductance parallel and perpendicular to the $[1\bar{1}0]$ direction, starting with an initial coverage (before annealing) of 3 ML is shown in Fig. 1. These curves are reversible and dominated by an abrupt change at a temperature of 78 K separating a high temperature region with small conductance anisotropy (factor 5 at the step, factor 1.5 above 100 K, not shown) from the low $T$ region which is characterized by high anisotropy (factor 30 to 60). At temperatures below 78 K a stepwise increase of $\sigma_\parallel$ by typically a factor of 3 is observed, whereas $\sigma_\perp$ drops sharply by a factor of 2 to 10. At these temperatures $\sigma_\parallel$ can well be described by $\sigma_\parallel = A + B \times T^{-n}$ with $n$ close to 1 [see Fig. 1(c)]. This decrease of $\sigma_\parallel$ as a function of temperature contrasts with the increase above the jump at 78 K, indicating thermally activated behavior above this threshold. $\sigma_\perp$, on the other hand, is thermally activated in both temperature regimes. As mentioned, the size of the step at 78 K in this direction varied on different samples. Whereas for large steps the anisotropy reached its high temperature limit of 1.3 to 1.5 immediately above 78 K, this value was reached for the smaller steps more gradually, typically around 100 K. This indicates that for $\sigma_\parallel$ defects play some role. For $\sigma_\parallel$, however, the optimal conductance values did not vary between different samples, and neither the abrupt changes seen in the conductance at 78 K nor the temperature dependence of $\sigma_\parallel$ below 78 K can be explained by defects.

From STM investigations of the identically prepared Si(557) surface covered with Pb we learn that the jumps in conductance are related to a structural phase transition in the annealed Pb monolayer. Figure 2 shows STM of the clean Si(557) surface that consists of an alternating arrangement of short (111) and (112) facets [16] with an

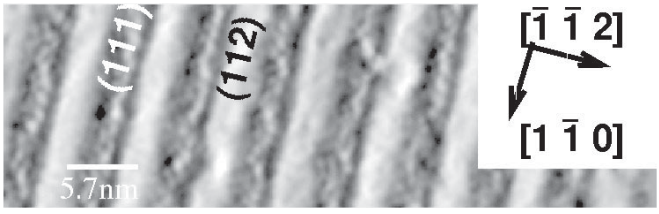


FIG. 2. STM picture (derivative) of the clean Si(557) surface (50 × 15 nm). Sample bias voltage +2 V, 0.5 nA.

average hill-valley spacing of 57 Å. The model of Ref. [16] is also supported by LEED [17–19].

After adsorption of Pb at low temperatures and annealing for 15 min to 640 K, STM reveals the characteristic chain structure shown in Fig. 3 with an average spacing between the chains of 14 Å, which is destroyed by annealing at 10 to 20 K higher temperatures. The surface shown in Fig. 3 is completely covered with Pb, and all chain structures are Pb induced. This is obvious from the disappearance of the double-line structure on the clean Si(557) surface, which is attributed to the (112) facets, but also from small minority areas, where, presumably induced by defects, Pb is desorbed completely, and bare (111) or (112) facets are visible [see Figs. 3(c) and 3(d)]. These chains must be responsible for the metal-insulator and semiconductor-insulator transitions of conductance along the $[\bar{1}\,\bar{1}\,2]$ and $[1\bar{1}0]$ directions, respectively. As

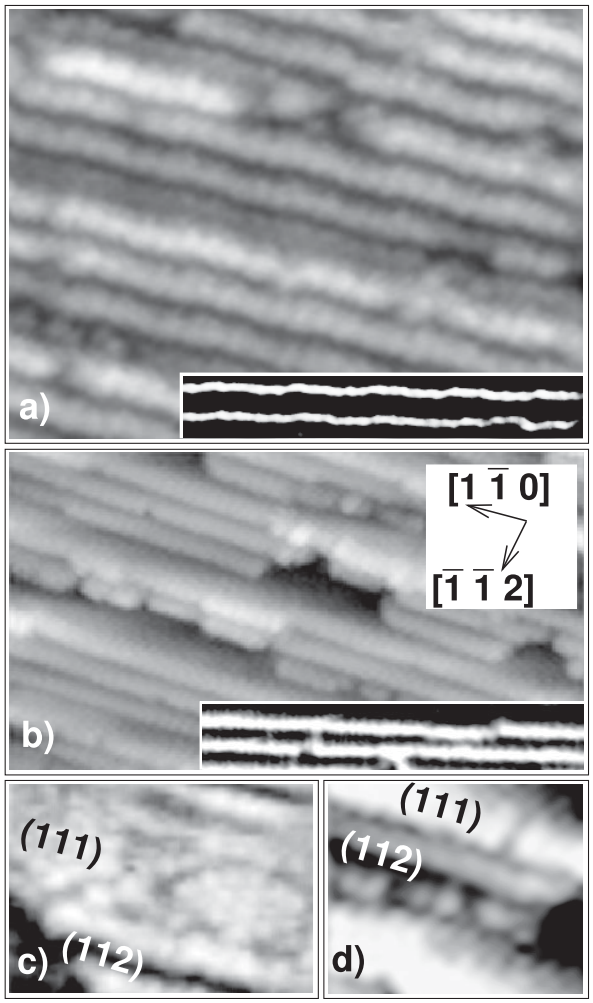


FIG. 3. STM pictures of the chains after adsorption of 10 ML Pb/Si(557) and annealing to 640 K ($U = 0.5$ V $I = 1$ nA) (a) $T = 40$ K, size $22 \times 16$ nm$^2$, (b) $T = 100$ K, size $37 \times 21$ nm$^2$. (c) and (d) at defect sites in the layers used in (a) at 40 K and in (b) at 100 K, demonstrating comparable quasiatomic resolution at both temperatures. Insets: Relief mode, emphasizing the weak modulation that is absent at 100 K.

judged from chains ending at small clean $7 \times 7$ islands, the bright chains must be located on the (111) facets or the edge between the two facets, whereas the other chains must be on the (112) facets.

Even at a temperature of 40 K these chains contain a lot of defects that limit the typical undistorted length of a chain to typically 30 nm, with the bright chains containing typically less defects than the others. Whereas the chain separation has a well-defined value, the stacking sequence normal to the chains seems to follow the local variation of facet sizes so that it is not long range ordered. Together with the step and kink structure of the substrate (not shown), these findings exclude the possibility of a macroscopic extension of undistorted chains from one contact to the other of the conduction measurements.

Nevertheless, the formation of the Pb-induced chain structures is intimately related to the observed behavior of conductance, and, in particular, to the drastic changes in anisotropy. The abrupt changes observed at $T_c = 78$ K cannot be explained by chain formation alone, but must be due to changes in local structure and/or to a possible structural phase transition. Indeed, clear changes in the local correlations become visible by taking STM images above and below $T_c$, i.e., by filling the cryostat either with $l$He or with $l$N$_2$ so that lowest temperatures on the sample of 40 and 100 K were obtained, respectively, [see Figs. 3(a) and 3(b)]. To examine correlation effects along and between the wires, one-dimensional Fourier transformations along and perpendicular to the chain structures were carried out of representative STM areas. The results are shown in Fig. 4 for a typical single scan in the top part on linear scale. Averages over an area of $40 \times 40$ nm$^2$ are shown on log scale in the lower two panels.

Starting with the direction normal to the chains (left part of Fig. 4), for both temperatures a clearly enhanced Fourier component $\Gamma_1$ is seen that corresponds to the average hill

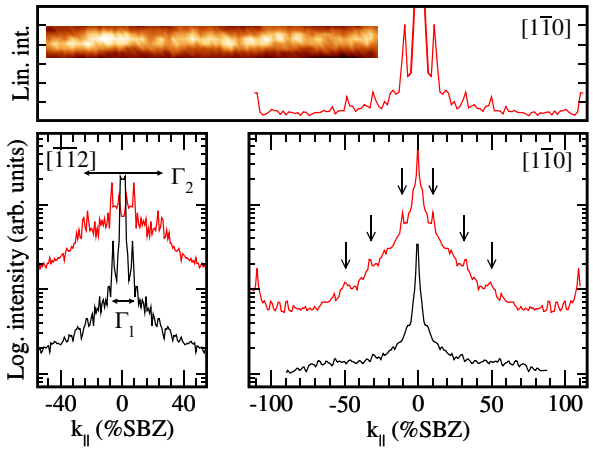


FIG. 4 (color online). Lower panels: Fourier transformations of line scans from STM pictures at 100 K (lower curves) and at 40 K for the direction perpendicular and parallel to the steps, respectively. In the top panel a single atomic chain and its Fourier transformation on linear scale is shown.

and valley spacing of 57 Å, i.e., to the periodicity of the clean Si(557) surface. For $T = 40$ K an additional component $\Gamma_2$ is seen, which corresponds to the 14 Å spacing of the Pb wires.

Parallel to the chain structure, the Fourier transforms calculated from 40 K STM images show, in contrast to those of STM images taken 100 K, an additional periodicity with a fundamental wavelength of 10 times the next neighbor separation of Si, together with higher harmonics. The peak at 110% with respect to the size of the surface Brillouin zone (%SBZ) corresponds to the nearest-neighbor spacing of Pb with approximately the bulk Pb lattice constant. No correlation of this periodicity between different chains was found, consistent with the invisibility of this modulation in LEED, as checked. The modulation of the chains is weak, as obvious from Figs. 3(a) and 4. It cannot be induced by missing Pb atoms, as seen, e.g., for the case of Ga on Si(112) [20,21], but rather by a modulation of the local position of adatoms, most likely due to the misfit between Si and Pb lattice constants. Since the lattice constant of Si is 9% larger than the lattice constant of Pb, registry between the ideal Si and Pb lattice is obtained every ten Si atoms, which agrees well with the tenfold periodicity found.

Above $T_c$, the still existing chain structure appears to be strictly straight and lacks atomic resolution, characteristic for a locally fluctuating chain system. Thus when going through the phase transition, it seems to be the locking of the chains into the high order commensurate superperiodicity, coupled with a regular separation between the Pb-induced chains, that cause the switching from low to high anisotropy and into a highly conducting state along the chains with a ''metallic''-like temperature dependence. This mesoscopic modulation sets, by backfolding the band structure along the chains, a lower limit of the effective wavelength of electrons at $E_F$ to twice the modulation period. This mechanism may be responsible for making electrons at $E_F$ unsusceptible to local defects on the atomic scale along the chains.

The sharp drop of conductance normal to the Pb chains, $\sigma_\perp$, below $T_c$ that amplifies the strong conductance anisotropy, is indicative of a strongly enhanced localization of the electrons in the direction normal to the wires, and leads to quasi-one-dimensional behavior. The conductance behavior in this highly anisotropic state may be a candidate for Luttinger liquid behavior in coupled chains [22]. However, the quantitative properties deviate clearly from the predictions for dc conductance in a Luttinger liquid, even in the presence of defects [23], since a simple power law cannot be fitted to the data of $\sigma_\parallel$ below $T_c$. Only if we neglect the relatively large constant contribution to conductance, the $1/T$ behavior of $\sigma_\parallel$ is indicative of a Luttinger liquid with strong electron interactions of fairly long range. Significant coupling between the chains is indicated by the nonzero value of $\sigma_\perp$ and its increase as a function of temperature.

Nevertheless, since we observe the quasi-one-dimensional conductivity down to 4 K, the energy scales for two-dimensional coupling are extremely small (of the order of a few Kelvin or even less) compared with other quasi-one-dimensional conductors [24]. This suggests that we have found a system with almost ideal one-dimensional conductive properties.

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