DS 40: Metallic nanowires on the atomic scale (joint session with O)

Time: Friday 9:30–13:15 Location: H 2032

Invited Talk DS 40.1 Fri 9:30 H 2032

From 2D to 1D: Honeycomb crystals and their nanoribbons — •Friedhelm Bechstedt — Friedrich-Schiller-Universitaet Jena, Germany

Metal-induced quantum wires are usually prepared on Si and Ge surfaces. Novel two-dimensional (2D) sheet crystals silicene, germanene and stanene as well as their functionalized counterparts are prototypes to study such atomically-thin layer systems.

Their exotic properties are studied using modern electronic-structure methods and discussed in the light of available experiments:

(i) Despite partial sp^3-bonding Dirac cones appear in their band structure similar to the sp^2-bonded graphene.

(ii) The infrared absorbance is given by the Sommerfeld fine-structure constant.

(iii) Chemical functionalization opens significant fundamental gaps. Excitons occur with giant binding energies.

(iv) A quantum spin Hall phase is due to spin-orbit interaction.

According to recent predictions one-dimensional structures, i.e., nanoribbons, should conduct electricity with 100% efficiency at room temperature with zero resistance along their edges. The predictions are critically discussed. The influence of magnetic ordering of edge states and external electric fields are investigated.

DS 40.2 Fri 10:00 H 2032

Impurity-mediated early condensation of an atomic layer electronic crystal: oxygen-adsorbed In/Si(111)-(4x1)/(8x2) — •Stefan Wippermann[1], Wolf Gero Schmidt[2], Deok Mahn Oh[3], and Han Woong Yeom[3] — [1]Max-Planck-Institut für Eisenforschung GmbH, D-40237 Düsseldorf, Germany — [2]Universität Paderborn, D-33098 Paderborn, Germany — [3]Pohang University of Science and Technology, Pohang 790-784, Korea

While impurities have been widely known to affect phase transitions, the atomistic mechanisms have rarely been elucidated. The self-assembled In/Si(111)-(4x1) nanowire array is an extremely popular model system for one-dimensional electronic systems and features a reversible temperature-induced phase transition into a charge density wave (CDW) ordered state, a representative electronic phase.

We present a joint experimental and *first principles* study, demonstrating oxygen impurity atoms to condense the In/Si(111) nanowire array locally into its CDW ordered ground state, even above the transition temperature. Interestingly, CDW ordering is not induced by single impurities, but instead by the cooperation of multiple impurities. The mechanism is explained as a coherent superposition of the local impurity-induced lattice strain, stressing the coupled electronic and lattice degrees of freedom for CDW ordered phases.

DS 40.3 Fri 10:15 H 2032

Transport in spatially confined anisotropic systems — •Frederik Edler[1], Ilio Miccoli[1,2], Herbert Pfnür[1], and Christoph Tegenkamp[1] — [1]Institut für Festkörperphysik, Univ. Hannover, DE — [2]Dept. Innovation Engineering, Univ. Salento, IT

Atomic chain ensembles are 1D-prototype systems with intriguing electronic properties, e.g. Peierls driven metal-insulator transitions (MIT). While such inherent instabilities can be probed smartly by surface transport, details of the phase transitions depend crucially on atomic-sized imperfections. In order to correlate such imperfections (including finite size effects) with transport properties, a spatial constriction of the electron paths is mandatory, e.g by using appropriately designed templates.

The In/Si(111) system reveals a strong anisotropy and has been comprehensively studied of the last years. We used it here as a benchmark system to investigate systematically the effects of confinement as well as of different contact geometries which is finally important to deduce correctly the resistivity components from resistance measurements. While spatial constrictions were achieved using Si(111)-mesas structures, various 4-point probe geometries could be realized by means of a 4-tip STM/SEM system. The anisotropy of the In-4×1 has been quantified by rotating the tips gradually in squared configuration. Indeed, the sensitivity was increased by one order of magnitude by performing the transport experiments on confined areas. Furthermore, first studies of the MIT tuned by adsorption of, e.g. oxygen, have been performed and will be discussed.

DS 40.4 Fri 10:30 H 2032

Ultrafast dynamics of (quasi-1D) Pb overlayers grown on flat and vicinal Si(111) — •Abdul Samad Syed[1], Vesna Mikšić Trontl[1], Manuel Ligges[1], Mathias Sandhofer[1], Ishita Agarwal[1], Isabella Avigo[1], Daniel Lükermann[2], Christoph Tegenkamp[2], Herbert Pfnür[2], and Uwe Bovensiepen[1] — [1]Fakultät für Physik, Universität Duisburg-Essen — [2]Institut für Festkörperphysik, Leibniz Universität Hannover

Due to real space anisotropy of the vicinal Si(111) surfaces, hot electrons can be expected to exhibit different dynamics along and perpendicular to the steps [1] as compare to the Si(111) flat surface. We made a comparative study of Pb overlayer structures grown on vicinal Si (557) and flat Si (111) using femtosecond time- and angle-resolved two-photon photoemission. We mapped the unoccupied electronic band structure near Γ and find that both systems have two unoccupied states at $E-E_F$=3.3 and 3.5 eV. In pump-probe experiments combined with a position sensitive electron time of flight spectrometer we analyze the ultrafast momentum dependent electron dynamics along two in plane directions. On vicinal surfaces we observe a specific, momentum dependent population dynamics which are absent on the flat surface. This signature shows a delay in population build up of 5 fs as a function of angle with respect to the terrace direction. We assign this behavior to step-induced scattering. We gratefully acknowledge funding by the DFG through FOR1700.

[1] Roth et al., Phys. Rev. Lett. 88, 096802 (2002)

DS 40.5 Fri 10:45 H 2032

Observation of correlated spin-orbit order in a strongly anisotropic quantum wire system — •Christian Brand[1], Monika Jäger[1], Herbert Pfnür[1], Gabriel Landolt[2,3], Hugo Dil[2,4], Stefan Muff[2,4], Tanmoy Das[5], and Christoph Tegenkamp[1] — [1]Institut für Festkörperphysik, Leibniz Universität Hannover, Germany — [2]Swiss Light Source, Paul Scherrer Institut, Villigen, Switzerland — [3]Physik-Institut, Universität Zürich, Switzerland — [4]Institute of Condensed Matter Physics, École Polytechnique Fédérale de Lausanne, Switzerland — [5]Theoretical Division, Los Alamos National Laboratory, USA

The surface of 1.31 ML Pb on Si(557) reveals a highly anisotropic wire ensemble structure becoming insulating in the direction across the wires when cooling below 78 K (2D/1D transition) as seen by surface transport. The delicate interplay between the superlattice structure, band filling, and extremely large Rashba type spin-orbit interaction results in a highly correlated entangled spin- and charge-state. The spin texture close to the Fermi surface is found to be alternating and equidistant, thus Fermi nesting occurs in between bands with the opposite helicity. Furthermore, the interwire coupling has been gradually changed by adsorption of excess Pb nucleating preferentially at the step edges. The analysis of spin-resolved momentum distribution curves shows that Fermi nesting is preserved up to 0.2 ML. Both the spin-dephasing seen in ARPES as well as the increase of the spin-orbit scattering rates from former magneto transport measurements is quantitatively explained in the framework of a spin-orbit density wave.

DS 40.6 Fri 11:00 H 2032

Tuning the Playground for Spin-Polarization in Au-Induced Atom Chains on High-Index Silicon Surfaces — •Julian Aulbach[1], Joerg Schaefer[1], Steven C. Erwin[2], and Ralph Claessen[1] — [1]Physikalisches Institut and Röntgen Center for Complex Materials Systems (RCCM), Universität Würzburg, Germany — [2]Naval Research Laboratory, Washington DC, USA

Atomic wires on semiconductor substrates allow direct access to spectroscopic studies of the low-temperature ground state of quasi-one-dimensional systems, such as a charge density wave or a Tomonaga-Luttinger liquid. A particularly intriguing concept is the use of high-index silicon surfaces of the type Si(hhk), providing tunability with respect to terrace width and adatom coverage. As a specific representative, stabilization of the Si(553) surface by Au adsorption results in two different atomically defined chain types, one made of Au atoms and one of Si. The latter, situated at the step edges, forms a honeycomb nanoribbon. At low temperature these silicene-like ribbons develop a period tripling, previously attributed to a Peierls instability. Here we report evidence from scanning tunneling microscopy that

rules out this interpretation [1]. On the contrary, our results are in excellent agreement with density functional calculations [2], which reveal an antiferromagnetic ordered state, where every third Si atom at the step edge hosts a single electron [1]. Additionally we will also address the consequences for this spin ordering by varying the high index substrate.

[1] J. Aulbach et al., Phys. Rev. Lett. 111, 137203 (2013).
[2] S. C. Erwin and F. J. Himpsel, Nature Commun. 1, 58 (2010).

DS 40.7 Fri 11:15 H 2032

Vibrational properties and optical anisotropy of lead nanowires on Si(557) — •Eugen Speiser[1], Arne Baumann[1], Sandhya Chandola[1], Jochen Räthel[1], Daniel Lükermann[2], Christoph Tegekamp[2], and Norbert Esser[1] — [1]Leibniz-Institut für Analytische Wissenschaften - ISAS - e. V., Department Berlin, Schwarzschildstrasse 8, 12489 Berlin, Germany — [2]Institut für Festkörperphysik, Appelstraße 2, 30167 Hannover, Leibniz Universität Hannover, Germany

We use Raman spectroscopy and Reflectance Anisotropy Spectroscopy (RAS) to investigate the vibrational properties and anisotropic optical response of Pb nanowires on Si(557). This model system, which shows quasi-1D conductance below 78 K, consists of 1.31 ML of Pb on the Si(557) surface. The adsorption of Pb induces a refacetting of the surface into evenly stepped (223) facets, decorated by one Pb nanowire each. Above 78 K the 2D coupling between the individual wires increases and allows conductivity perpendicular to them. RAS measurements of the Si(557) surface before and after Pb deposition show that the adsorption of Pb clearly induces a reorganization of the surface. Both phases exhibit a strongly anisotropic optical conductance behavior and anisotropic optical transitions which can be associated with the Pb induced reformation of the surface. The Raman spectra show surface vibrational modes which are only present after Pb deposition. With theoretical calculations it is possible to elucidate the relation of the surface vibrational modes with atomic structure and propose structural models for the high and low temperature phases.

15 min. break.

DS 40.8 Fri 11:45 H 2032

Doping Induced 1D Plasmons in Ag Monolayer Stripes on Si(557) — •Timo Lichtenstein, Ulrich Krieg, Christoph Tegenkamp, and Herbert Pfnür — Leibniz Universität Hannover, Institut für Festkörperphysik, 30167 Hannover, Germany

We demonstrate here by testing the plasmonic properties for the system Ag/Si(557) that the interaction between adsorbate layers of transition metal atoms and strongly anisotropic surfaces can lead to various quasi-1D signatures, which, however, are not all necessarily metallic. Using low energy electron diffraction in combination with scanning tunneling microscopy and electron energy loss spectroscopy, we correlate the structure with the properties of low dimensional collective excitations, as measured with momentum and energy resolving electron loss spectroscopy. Semiconducting structures with double periodicity along the chains are formed for Ag coverages below 0.3 ML. At higher coverages, coupled with the onset of $\sqrt{3} \times \sqrt{3}$ order, metallic wires are formed. This is evident from the appearance of plasmonic losses, which show 1D dispersion only along the wires. This 1D property even persists up to 1 ML, where a densely packed array of metallic $\sqrt{3} \times \sqrt{3}$ stripes is formed. We show evidence that the metallic property is induced by an extrinsic doping process of excess Ag atoms localized at the step edges, which can be reversibly removed and added. With this system we were able to explicitly show that the 1D plasmon frequency depends on the electron density proportional to $\sqrt{n_e}$ also in the 1D case, and that the confinement of the electrons on the wires is also dependent on doping concentration.

DS 40.9 Fri 12:00 H 2032

Optical and electronic properties of quasi-1D gold nanowires on Si(553) surfaces — •Sandhya Chandola[1], Eugen Speiser[1], Conor Hogan[2], Svetlana Suchkova[1], Jochen Räthel[1], Julian Plaickner[1], and Norbert Esser[1] — [1]Leibniz-Institut für Analytische Wissenschaften - ISAS - e.V., Department Berlin, Schwarzschildstrasse 8, 12489 Berlin, Germany — [2]Institute for Structure of Matter, CNR-ISM, Via Fosso del Cavaliere, 00133 Rome, Italy

The structures of many 1D metallic nanowire systems have not yet been sufficiently clarified, such as gold nanowires on vicinal Si surfaces. Such structures are intrinsically anisotropic and can be investigated by Reflection anisotropy spectroscopy (RAS) which is a powerful optical technique for probing electronic states of surfaces. The optical response of the Si(553)-Au and hydrogenated Si(553)-Au surfaces are measured with RAS and compared with density functional theory simulations. Good agreement between experiment and theory is obtained. Local structural elements such as the Si honeycomb chains and the gold atomic wires, yield distinctive features in the optical spectra. By comparing the optical response of the freshly prepared and hydrogenated Si(553)-Au surfaces, the spectral features can be directly attributed to particular structural elements on the surface. This combination of experiment and theory is very useful in identifying specific structural sites on the surface, which generate distinctive features in the optical response. The surface will be used to attach molecules such as 3,4-toluenedithiol. The ordered array of the molecules could act as a template for further functionalization.

DS 40.10 Fri 12:15 H 2032

Vibrational properties of Au nanowires on Si(553) and Si(111) surfaces — •Sergej Neufeld[1], Simone Sanna[1], Jochen Räthel[2], Norbert Esser[2], and Wolf-Gero Schmidt[1] — [1]Lehrstuhl für Theoretische Physik, Universität Paderborn — [2]Leibniz-Institut für Analytische Wissenschaften - ISAS - e.V., Berlin

Metallic nanowires on semiconducting substrates such as silicon and germanium have been attracting considerable interest in the last decade. Besides various potential applications as non ohmic conductors, they are candidate systems for the demonstration of the basic concepts of one-dimensional physics such as electron correlation and Luttinger liquid behavior. In particular, the phase transitions observed on these systems have been controversially discussed and are still poorly understood. Self organizing gold chains at vicinal surfaces such as the Si(553) and Si(111) are of particular interest, as the use of stepped templates allows to vary the geometric parameters and, thus, tune the inter-chain coupling. While well-established microscopic structural models of Au nanowires on various Si surfaces based on density functional theory are available in the literature, few is known about their vibrational properties. In this work, the phonon eigenmodes and eigenfrequencies of the Au/Si(553) and Au/Si(111) wires are calculated from first-principles at the center of the Brillouin zone. Several surface localized phonon modes are found, whose phonon frequencies can be directly compared with the spectra obtained by Raman measurements. Raman scattering efficiences are calculated in order to facilitate the comparison between experiment and theory.

DS 40.11 Fri 12:30 H 2032

Plasmonic excitations in Au/Si(553) and Au/Si(775) — •Timo Lichtenstein[1], Julian Aulbach[2], Jörg Schäfer[2], Christoph Tegenkamp[1], and Herbert Pfnür[1] — [1]Leibniz Universität Hannover, Institut für Festkörperphysik, 30167 Hannover, Germany — [2]Physikalisches Institut and Röntgen Center for Complex Materials Systems (RCCM), Universität Würzburg, 97074 Würzburg, Germany

Si(553) and Si(775) surfaces are highly stabilized by Au adsorption resulting in chain reconstructions of Au and Si atoms. For low temperatures the chains develop a change in periodicity not because of a Peierl's transition but because of frozen spin-polarization. Therefore, they remain metallic at low temperature. Here we study the metallicity of these systems by investigating the plasmons of the spin-split bands.

The sample quality was controlled with SPA-LEED. The plasmon dispersion was then investigated via a combination of EELS and SPA-LEED setup providing both high energy and momentum resolution. Measurements were carried out at room temperature and at 77 K.

Similar to Au/Si(557) [1], the dispersion for Au/Si(553) and Au/Si(775) is also linear for $k_{||} > 0.07\,\text{Å}^{-1}$, a typical signature in 1D. Compared to Au/Si(557) the slope is decreased by a factor of about 2, reflecting the lower electron density of $1 \times 10^7\,\text{cm}^{-1}$. For lower $k_{||}$ the dispersion relations saturate at 200 meV (150 meV) for Au/Si(553) (Au/Si(775)), indicative of quantum well states perpendicular to the steps expected for electronically well separated wires [2].

[1] T. Nagao et al., Phys. Rev. Lett. 97(11), 116802 (2006).
[2] U. Krieg et al., J. Phys.: Condens. Matter 25(1), 14013 (2013)

DS 40.12 Fri 12:45 H 2032

Structural Fluctuations on Si(553)-Au — •Ingo Barke[1], Stefan Polei[1], Paul C. Snijders[2], and Karl-Heinz Meiwes-Broer[1] — [1]University of Rostock, Institute of Physics, 18051 Rostock, Germany — [2]Materials Science and Technology Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA

The (1x3) reconstruction on Si(553)-Au can be excited to a (1x2) structure by charge injection from the tip of a scanning tunneling microscope [1,2]. Time-resolved measurements enable access to the system's dynamics revealing rapid fluctuations due to a competition between excitation and decay. In this contribution we focus on the time-dependent response to the specific charge injection site. Two distinct locations of high excitation efficiency are identified. This site specific behavior is also found in spatially resolved current-distance curves which are further employed for a quantitative analysis of the current-dependent structural transition of this system. The results are discussed in view of structural and electronic ground state properties of Si(553)-Au.

[1] S. Polei, P.C. Snijders, S.C. Erwin, F.J. Himpsel, K.-H. Meiwes-Broer, and I. Barke, Phys. Rev. Lett. 111, 156801 (2013).

[2] S. Polei, P.C. Snijders, K.-H. Meiwes-Broer, and I. Barke, Phys. Rev. B 89, 205420 (2014).

DS 40.13 Fri 13:00 H 2032

Tb silicide nanowires on Si(001) - a one-dimensional metal? — •Stephan Appelfeller, Martin Franz, Christopher Prohl, Jan Grosse, Zeno Diemer, and Mario Dähne — Inst. f. Festkörperphysik, TU Berlin, Hardenbergstr. 36, 10623 Berlin

Rare earth metals are well known for their formation of metallic bulk silicides with low Schottky-barrier heigths to n-type Si. Using appropriate preparation conditions, some rare earth metals, e.g. Tb, are forming silicide nanowires on Si(001) by self-assembly, which have widths of only a few nanometers and lengths of several hundred nanometers. Here, the structural and electronical properties of Tb silicide nanowires are elucidated.

The structural information gained by scanning tunneling microscopy indicates that the Tb silicide nanowires consist of metallic hexagonal $TbSi_2$. Scanning tunneling spectroscopy confirms this finding by showing metallic behavior. Furthermore, angle resolved photoemission data obtained at the UE56/2 PGM1 beamline of BESSY clearly reveal a one-dimensional metallic band structure without dispersion perpendicular to the nanowire main axis. Thus, Tb silicide nanowires are promising for future investigations of unique phenomena of one-dimensional metals, such as the Peierls transition.

This work was supported by the DFG, FOR 1700, project E2. We kindly acknowledge the support of K. Horn and coworkers and of BESSY.