Wednesday Morning, October 17, 2007

Nanometer-scale Science and Technology

Room: 616 - Session NS+EM-WeM

Nanoscale Devices and Nanowires I

Moderator: S. Pang, University of Michigan, C. Eddy, Naval Research Laboratory

8:00am **NS+EM-WeM1 Self-Organization of SiGe Quantum Dots Grown on Ultrathin Si Nanomembranes**, ***F.S. Flack***, *C.S. Ritz, M.G. Lagally, H.J. Kim, K. Turner*, University of Wisconsin-Madison, *M. Huang, F. Liu*, University of Utah

Self-assembly in nanostructures is a linchpin of the bottom-up design technique essential to the advance of nanoscale fabrication. In particular, the self-assembly demonstrated by quantum dots (QDs) in strain-mismatched systems has potential for applications in lasers, high-density memory, and thermoelectric devices. Self-assembled arrays of QDs have been fabricated by several techniques with varying degrees of success and usability. We demonstrate an entirely new route for investigating the nucleation and ordering of QDs: growth on ultrathin semiconductor nanomembranes, substrates that are so thin, usually on the order of tens of nm, that they allow the strain created by a QD to penetrate the entire structure,. Such freestanding thin films are truly compliant and, when thin enough, regions of high strain will bend. Thus, we must address the effects of both strain and bending on the preferential nucleation of SiGe QDs. Tethered Si nanomembranes (cantilevers, ledges, wires, and ribbons) with thicknesses ranging from 20 nm to 60 nm are fabricated from silicon-on-insulator (SOI) substrates. SiGe QDs are then grown epitaxially by ultrahigh vacuum chemical vapor deposition. To ensure appropriate strain, the QDs are grown to have dimensions of the same order as the membrane thickness - roughly 8 nm in height. CVD allows for QD nucleation simultaneously on both sides of the membrane, so that nucleation of a QD on one side influences nucleation on the other. In addition, the nanomembranes are thin enough to be semi-transparent in an SEM, granting us a direct view of the alignment of QDs on the top surface to those on the bottom. We model this growth system with finite element analysis and see that a SiGe island nucleated on the top creates regions of high strain on the bottom along preferential crystallographic directions. These strained regions act as sites for preferential nucleation for QDs on the bottom, which will then seed the next QDs on the top layer and so on to create highly ordered, anticorrelated, arrays on both the top and bottom of the membrane. We discuss the simulations and observations in the limits of QD nucleation due to substrate bending and strain modulation. Research supported by DOE and AFOSR.

8:20am **NS+EM-WeM2 Synthesis of $Si_{1-x}Ge_x$ Nanowire Alloys by Chemical Vapor Deposition**, ***S.G. Choi***, Los Alamos National Laboratory, *P. Allea*, Arizona State University, *S.B. Chikkannanavar, E. Akhadov, S.T. Picraux*, Los Alamos National Laboratory

There is an increasing interest in semiconductor nanowires (NWs) as a result of their unique physical properties which have resulted in new conceptual devices at the "nano" scale. Among a large number of NWs explored so far, Si and its related NWs have received much attention, in part due to their potential for easy integration into the well-developed Si microelectronics. Recently, attention has been given to SiGe alloy NWs which offer bandgap tuning from 0.7 to 1.1eV and possible applications in various devices. In order to synthesize these SiGe alloy NWs in a controlled manner and to realize nanoscale devices with optimum performance, it is important to understand the nature of alloy NWs growth. Although the two binary endpoints - Si and Ge NWs - have been well investigated, studies of SiGe alloy NWs are still in a formative stage. In this work, we studied effects of growth conditions on the structural characteristics of SiGe alloy NWs. SiGe alloy NWs were grown by chemical vapor deposition (CVD) on Si(111) substrates by the vapor-liquid-solid (VLS) mechanism. Au nanoparticles were used as the catalysts, and SiH_4 and GeH_4 were used as the source gases. Partial pressures were controlled precisely by mass-flow controllers for the flow rate of individual gases and a pressure controller for the total process pressure. NWs were grown at temperatures between 450 and 600°C. Morphology and composition of the grown NWs were investigated by scanning electron microscopy (SEM) and energy dispersive x-ray spectroscopy (EDXS), respectively. The NWs are observed to become more tapered as growth temperature or Ge composition is increased. Also for the same Au nanodot seeding conditions, the epitaxial Ge-rich alloy NWs grow primarily in the four <111> directions with a substantial fraction of these being vertical [111]-directed NWs, whereas the Si-rich alloy NWs exhibit a noticeable amount of the smaller diameter <110> oriented NWs as well as the four <111> NW orientations. In this work, we examined possible dependences of composition on: (1) diameter of NWs, (2) growth orientations, (3) growth temperature, (4) ratio of GeH_4 to the total partial pressure (i.e., $P[GeH_4]/(P[SiH_4] + P[GeH_4])$. In this presentation, we will contrast alloy growth with Si and Ge end point growth, and discuss possible mechanisms for explaining the observed effects of growth parameters on composition, morphology, and structure of SiGe alloy NWs.

8:40am **NS+EM-WeM3 In Situ Kinetic Measurements during the Nucleation and Growth of Si and Ge Nanowires**, ***F.M. Ross***, IBM T. J. Watson Research Center **INVITED**

In this presentation we will discuss the growth of epitaxial nanowires in Si and Ge using Au as the catalyst, focusing on the kinetic processes that influence nucleation and wire shape. We grow wires in an environmental TEM, which has capabilities for evaporating Au onto a clean Si substrate and for introducing the precursor gases while the sample remains under observation. In situ video rate imaging allows us to measure nucleation events and growth kinetics and to observe structures during growth. We will start by showing the nucleation of Si nanowires within the catalyst particles, and will discuss the buildup of supersaturation that leads to nucleation. After nucleation, the variation of growth rate with pressure, temperature and droplet size allows us to determine the rate limiting step and evaluate the relevance of curvature-driven effects to wire growth. For Si wires, the simple picture that results is complicated by some interesting phenomena caused by the high mobility of Au on the wire surface. And for Ge wires, we show that the growth-driven supersaturation can stabilise the droplets and allow growth far below the eutectic temperature. We finally discuss the growth of hybrid nanowires composed of group IV and group III-V components, showing how the balance of interface energies determines the overall structure. Thus we find that nanowires provide a unique window into fundamental crystal growth processes, as well as an opportunity to fabricate precisely controlled structures for novel applications.

9:20am **NS+EM-WeM5 Self-Catalyzed Growth of Defect-Free Indium Phosphide Nanowires on Silicon**, ***R.L. Woo***, University of California, Los Angeles, *Y. Kobayashi, T. Mallouk*, Penn State University, *R.F. Hicks*, University of California, Los Angeles

Compound semiconductor nanowires exhibit promising properties for high-speed nanoelectronic devices. However, in order to realize their full potential, growth processes must be developed for the precise control of the nanowire shape, density, uniformity, and crystalline quality. In this study, we report on the fabrication of indium phosphide nanowires on silicon (100) and (111) by metalorganic vapor-phase epitaxy. Nanoscale indium droplets were used instead of gold catalyst to nucleate wire deposition. High-resolution transmission electron microscopy with selected area electron diffraction have revealed that the InP nanowires are free of crystal defects and grow along either the <110> or the <113> axis. This may be contrasted to gold catalyze growth, where the preferential orientation is <111>, and there is a relatively high density of stacking faults. Through careful control of the substrate preparation and the MOVPE process conditions, it has been possible to grow vertical InP nanowires of uniform diameter and lengths over 1.0 micron. At the meeting, we will present data on the novel electrical and optical properties of the indium phosphide nanowires.

9:40am **NS+EM-WeM6 Plasma-stimulated Control of Silicon Nanowire Nucleation, Orientation and Growth Kinetics**, *P. Aella, W.T. Petuskey*, Arizona State University, ***S.T. Picraux***, Los Alamos National Laboratory

Plasma-enhanced chemical vapor deposition is shown to significantly alter the nucleation rate and activation energy for vapor-liquid-solid (VLS) growth of silicon nanowires compared to thermal growth, providing new control over nanowire morphologies and new insight into the rate-limiting mechanisms of VLS growth. Initially, catalytic gold films (0.5 - 2 nm thick) were thermally evaporated onto hydrogen terminated Si (100) substrates at room temperature in a UHV deposition system. Subsequently, Si nanowires were grown in a cold wall reactor at 0.5 Torr in atmospheres of 10% SiH4 in H2 between 350 to 510ºC and RF plasma powers of 2.5 to 10 W. SEM images show that thermally grown nanowires on Si (100) substrates nucleate and grow predominantly in <111> directions. In contrast, plasma stimulation significantly enhances the nucleation rate of smaller diameter <110> Si nanowires and also reduces coarsening of Au dots. A two step growth process is demonstrated whereby initial plasma excitation nucleates <110> nanowires followed by thermal growth to preferentially form a high density of small diameter <110> nanowires on Si (100) surfaces, greatly limiting the large diameter <111> nanowire formation found under thermal growth conditions with identical Au seeding. This demonstrates the overall

effect of the plasma on shortening nucleation times, favoring thinner wires, and thereby dominating the rest of the growth process. A comparison of the growth rate vs. temperature for both <111> and <110> nanowires shows a large reduction in the activation energy (from 0.74 to 0.26 eV) due to the plasma. The overall growth rate is also greatly enhanced at low temperatures by plasma excitation, with growth rates at 350ºC an order of magnitude greater than for thermal growth. Under our low temperature thermal conditions the predominant source gas is silane, while in the case of plasma stimulation SiH3 radicals are also present. Our results unequivocally demonstrate that the rate limiting step for Si nanowire growth under these conditions is due to the kinetics of silicon incorporation at the vapor-liquid interface and not at the liquid-solid interface as has also been previously proposed in some cases. Based on our measured incorporation coefficients and activation energies under thermal and plasma-enhanced growth we suggest the first model for the rate-limiting kinetic steps for Si nanowire growth by the VLS mechanism.

10:40am **NS+EM-WeM9 Nanowires in Nanoelectronics: Problems and Promise**, ***D.K. Ferry***, Arizona State University **INVITED**

Progress in microelectronics has generally followed the well known scaling rules known as Moore's Law. By the end of this decade, we will approach some well recognized limits in traditional semiconductor devices. Nanowires have been put forward as a new technology with new promise to extend nanoelectronics. For this to be the case, the nanowires must fit into the scaling rules and must offer important new options, primarily in circuit cleverness. In this talk, I will review the scaling rules, and where they have led us, then discuss how the constraints of these rules, particularly Si area cost, dictate how new technologies can be used. These suggest that the impact of nanowires will likely be in providing new options for architectural revolutions, as opposed to merely clever new devices.

11:20am **NS+EM-WeM11 Electrical and Mechanical Characterization of Nanowire Properties using In-Situ SEM**, ***D.F. Ogletree***, Lawrence Berkeley National Laboratory

Nanowires have unique electrical and mechanical properties with a wide range of potential applications in electronics, opto-electronics and nano-mechanics. Local measurements of the electrical and mechanical properties of individual nanowires in controlled environments are required to develop these applications and to optimize nanowire growth conditions. A flexible system for nanowire characterization based on a high-resolution environmental scanning electron microscope (SEM) has been developed combining sample heating in controlled gas environments with nano-positioning of local probes. This system has been used to investigate the evolution of size-dependent nanowire mechanical properties between room temperature and the melting point of the nanowires.

11:40am **NS+EM-WeM12 Four Independent STM Navigated by High Resolution UHV SEM: Transport Measurements on In-Situ Grown Titanium Silicide Nanowires on Si(111)**, ***J. Koeble***, *M. Maier*, Omicron NanoTechnology, Germany, *B. Grandider*, IEMN, Lille, France

A major challenge in Nanotechnology is the incorporation of single nano-devices into larger integrated circuits. Traditional instrumentation suffers from one fundamental issue: How to cover the dimensional range of a fully integrated circuit down to the nanometer range (or even atomic scale) of single devices and have an adequate integrated navigation system. To meet these requirements, we have established and being advancing a new approach to integrating state-of-the-art SPM technology via high resolution electron microscopy and spectroscopy: (1) Bridging dimensions and rapid navigation; (2) Combining different surface analysis methods at the very same sample area to gain complementary information; (3) Integrated position-readout of sample and probe positioning; (4) Pushing each single technology to its inherent limits. The system facilitates four independent Scanning Tunnelling Microscopes and the UHV version of the Zeiss Gemini SEM column with ultimate resolution below 4nm for probe navigation and rapid localisation of sample features or devices. STM imaging is used to pro-actively position and contact the probe(s) on nano-devices. Using STM probe approach technology, a controlled electrical contact is ensured to finally perform a four-point measurement on the nano-scale. We report on electrical measurements on self-assembled titanium silicide nanowires (NWs) in-situ grown on a Si(111) surface. Transport measurements have been taken in 2-point and 4-point configuration. The transport measurements indicate metallic behavior for the silicide nanowires and that the NWs are electronically decoupled from the Si surface and reveal a Schottky barrier between the NWs and the Si surface.

12:00pm **NS+EM-WeM13 Anisotropic Plasmon and Electronic Structure of Ag Nanowires on Cu(110)**, ***P.T. Sprunger***, *I. Senevirathne, W. Zhao, B.M. Watson, O. Kizilkaya, A.K. Sekharan, R.L. Kurtz*, Louisiana State University

Epitaxial Ag nanowires have been found to self-assemble on Cu(110) for Ag coverages exceeding 1.2 ML. The electronic and plasmon loss structure of the nanowires have been characterized by ARPES and EELS. STM images reveal that Ag nanowires grown on Cu(110) are approximately 2 nm high and ~12 nm wide. The nanowires grow oriented with the long axis parallel to the [$\bar{1}$10] substrate direction and they have aspect ratios up to 20:1. The ARPES results show that the valence bands within the Ag nanowire are strongly anisotropic with clear band dispersion in the along-wire direction, but no dispersion in the across-wire direction. This strongly suggests that the valence electrons of Ag behave as quasi-one-D conductors along the wire yet confined with atomic-like states perpendicular. Fermi surface crossings have been observed, confirming that metallic behavior is realized along the wire axis. In accord with the ARPES measurements, EELS reveals that the plasmon excitation is red-shifted at the zone-center and is nearly dispersonless perpendicular to the nanowire direction. These results will be discussed in light of recent band-structure calculations of Ag nanowires and models for plasmon behavior in quasi-1D structures. We would like to acknowledge the support of the LSU CAMD synchrotron light source and the support of and LA-R&D and NSF through DMR-0504654.

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