CAREER/PECASE: Growth and Analysis of Novel Nitride Semiconductor Systems

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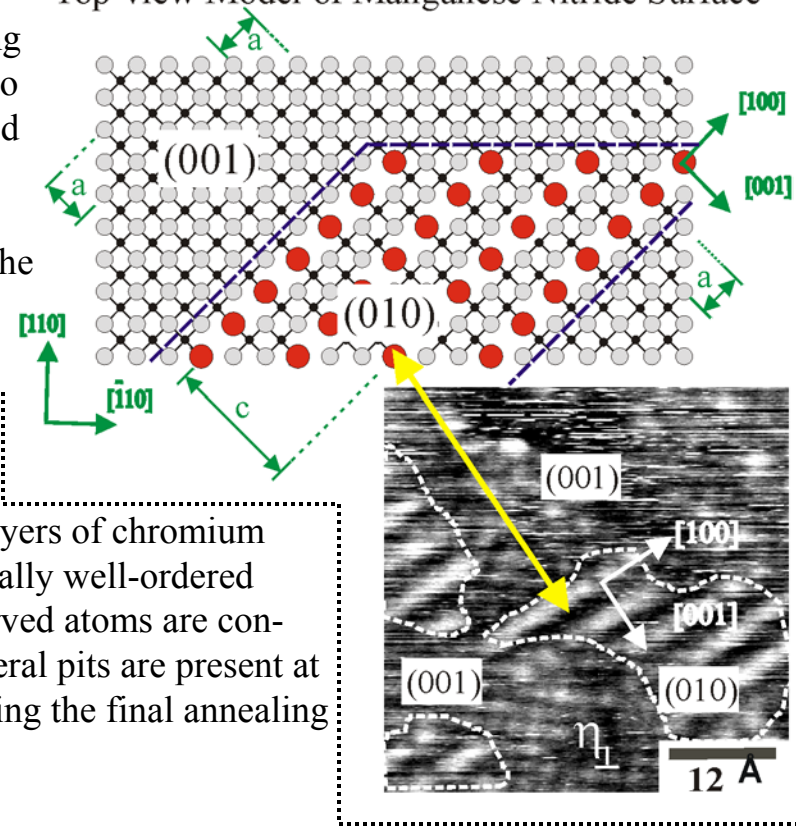
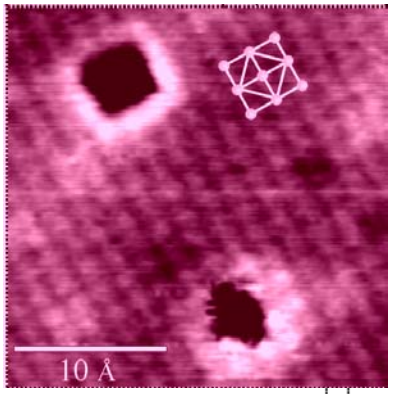
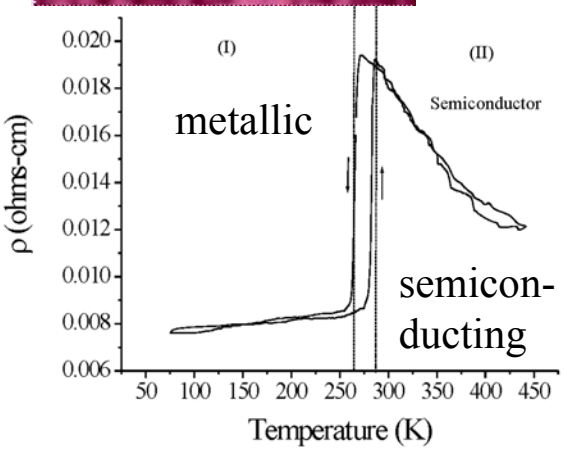
Transition Metal Nitride Phase Transition. MnN(001) surface is grown using MBE and has a simple rock-salt type structure. Annealing the sample results in a structural phase transition to Mn3N2 having two orientations – (010) and (001). The co-existing orientations are imaged by STM and presented at right in gray scale together with a structural model. The significance of this result is that we have observed, at the nanoscale, the new, phase-transformed, magnetic domain structure. The result is relevant for future possible uses of manganese nitride as the antiferromagnetic pinning layer in an exchange-biased multilayer.

Top-view Model of Manganese Nitride Surface





Metal-Semiconductor Phase Transition in Chromium nitride. We have grown high quality epitaxial layers of chromium nitride by MBE. STM shows an atomically well-ordered surface, which is seen at left. The observed atoms are considered to be the chromium atoms. Several pits are present at the surface which may have formed during the final annealing step.



Resistivity measurements were also performed on the samples as a function of temperature. Two regions - a linear and an exponential region - were observed, showing that the CrN sample has metallic behavior below ~ 265K and semiconducting behavior above ~ 285K. The semiconducting nature at 300K is consistent with STM data. The transition region shows thermal hysteresis with a width of ~ 20K. The significance of this work is that it links together the electronic properties with the known structural and magnetic properties of CrN. This work has been the project of Mr.C. Constantin.

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Transition metal nitrides are a novel and interesting class of materials. Study of their fundamental physical properties is of paramount importance for future technological applications. Two interesting materials are MnN and CrN. We have shown previously that different phases of manganese nitride – MnN, Mn_3N_2, and Mn_4N – can be grown specifically in MBE by controlling the Mn flux and substrate temperature. We have recently found that the Mn_3N_2 layer can also be produced directly from (001)-oriented MnN layer by means of annealing. The phase transition involves loss of N from the film. Two mixed orientations are observed for the Mn_3N_2 phase, as seen in the STM images. We are now beginning to have a more complete picture of the structural and magnetic properties of manganese nitride, as well as how to manipulate the phases, either by growing them directly, or else through annealing. While the transition from MnN -> Mn_3N_2 was shown previously for bulk material by another group [*K. Suzuki et al., J. Alloys & Compounds* ***306****, 66 (2000)*], we are the first to observe it for oriented, crystalline thin films using STM.

Since MnN and Mn_3N_2 are antiferromagnetic (aFM) materials, there is the possibility to utilize them as pinning layers in exchange-biased multilayers. The magnetic structure of MnN is quite different compared to Mn_3N_2, and their Neel temperatures are also different – 650K and 925K, respectively [*M. Tabuchi et al., J. Alloys and Compounds* ***210(1-2)****, 143 (1994)*]; but potentially both can be used to build a very unique device structure, namely, an all-manganese nitride exchange-biased device. Such a device would be possible by growing, on top of the MnN layer, a layer of ferrimagnetic Mn_4N. Such a uni-material device may have certain advantages, such as reduction of interfacial intermixing, resulting in improved device properties. The structure of the interface is considered to be important for exchange biasing. Since heating may be required to make a device, the thermal stability of the manganese nitride aFM layer is also important. This result is therefore significant since, as we show here for the bare surface, we know exactly what the structure after annealing is, both in terms of phase and orientation.

Chromium nitride also has very interesting properties. It is known to undergo a structural phase transition from face-centered tetragonal at high temperatures to orthorhombic at low temperatures. Theoretical work has linked this structural transition with the also-observed magnetic transition from paramagnetic (PM) at hi T's to aFM at low T's [*L. M. Corliss et al., Phys. Rev.* ***117****, 929 (1960); A. Filippetti and N. A. Hill, Phys Rev. Lett* ***85****, 5166 (2000)*].

Through our MBE growth of oriented, crystalline thin films of CrN, we have now been able to further link these transitions with a metal-semiconductor transition. The results of our study tie together the electronic, magnetic, and structural properties of this material. The electronic properties also lack explanation in terms of available theoretical models; thus, the results call the need for further theoretical work in order to explain these apparently correlated properties.

Another interesting point concerning our STM investigation of the CrN(001) surface is that we observe (more clear in other images than that shown here) long-range "topographic" distortions - the surface shows some undulations rather than being exactly "flat." These distortions are attributed to surface band bending, which implies that at 300K, CrN is a semiconductor, in agreement with resistivity vs. temperature data. Similar distortions were also observed in the case of semiconducting ScN(001). Furthermore, tunneling spectroscopy on CrN(001) shows a clear, but narrow, dip in the normalized conductance near the Fermi level, consistent with the small bandgap deduced from the resistivity data of 71.0 meV.

Use of these novel TM nitride materials in future devices requires that we develop a better understanding of their fundamental structural, magnetic, and electronic properties. This work is doing just that. Beyond the study of these binary TM nitrides, the knowledge gained in these studies is also helpful for the study of ternary TM nitride materials, such as MnGaN and CrGaN, which have potential spintronic applications. Work on those materials is also in progress.

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Graduate Education in Electronic Materials: Dissemination of Research Results/Presentation. Shown here are, from left to right, Costel Constantin (GA), Rong Yang (GA), Hamad Al-Brithen (GA), Muhammad Haider (GA), and PI Art Smith. The group attended the International Workshop on Nitride Semiconductors held in Pittsburgh, PA July 19-23, 2004 and made six presentations. The workshop was operated by the Materials Research Society.

ATOMS Outreach Program. Two students from Zanesville High School (Ohio) are being introduced to the world of nanoscience, shown here working with the scanning tunneling microscope and getting atomic-resolution images on April 22, 2004. The ATOMS program makes it possible for Southeastern Ohio students to "see" for themselves if atoms really exist by imaging them directly.

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The MBE-STM group, led by Prof. Art Smith, attended IWN-2004 which was held in Pittsburgh, PA this July. The conference was an excellent opportunity for the group to attend an international meeting on the topic of nitrides for both electronic/optoelectronic (biggest group) applications and also spintronic applications. Smith's group had a total of 6 presentations, 3 of which were in the "Magnetic Nitrides I" and "Magnetic Nitrides II" oral sessions, 1 in the "Surfaces & Interfaces" oral session, and 2 in the "Interface/Surface Physics" poster session. The topics of these talks included manganese nitride surfaces (Yang), MBE-SPM of GaCrN (Haider), metal-semiconductor phase transition of CrN (Constantin), STM and theory of GaN(001) 4x1 tetramer reconstruction (Al-Brithen and Sandler), and the structure of ScGaN (Constantin). The abstracts of these 6 and all the other presentations of this workshop can be found on the IWN-2004 website: http://www.mrs.org/meetings/workshops/2004/iwn/. Their abstract session identifiers are: B1.2, B1.6, B2.3, B3.2, P2.2, and P2.4.

Smith's outreach program – ATOMS – has been very successful during the last year. A second STM – the Nanoscope II – was employed for use in the high school classroom. Teachers were trained to use the Nanoscope II by a fellow teacher during a teacher instructional day during Fall 2003. The instructor had spent several weeks during summer 2003 preparing the STM for high school use. The good results using this instrument are evident from the facial expressions of two Zanesville, Ohio high school students using the instrument (shown here). Being able to image atoms in the classroom is hoped to motivate these students to pursue careers in science or engineering.