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Scanning Probe-Based Processes for Nanometer-Scale Device Fabrication

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Abstract

This is the final report of an LDRD program entitled "Scanning Probe-Based Processes for Nanometer-Scale Device Fabrication". This program intends to expand Sandia's expertise in scanning-probe based fabrication and characterization of nanostructures. Our object is to achieve an order of magnitude decrease in feature size compared to conventional fabrication technology. We are exploring approaches to nanostructure fabrication and characterization using scanning probe-based (STM, AFM). We also are developing numerical simulations of localized electric field and emission current to explore mechanisms and characterize limits to processing techniques. We emphasize novel fabrication processes and characterization of physical, chemical and electronic effects in nanostructures.

Introduction

Development of nanometer-scale technologies requires a novel physics base that includes fabrication processes, characterization techniques and materials properties allowing reliable performance of devices at this very small length scale. This program intends to expand Sandia's expertise in scanning-probe based fabrication and characterization of nanostructures. Our object is to achieve an order of magnitude decrease in feature size compared to conventional fabrication technology. This order of magnitude jump in our ability to make small structures opens new areas of fundamental physics research on the properties of mesoscopic structures, and enables new types of electronic and sensing devices with enhanced functionality, speed, and reliability. We are exploring approaches to nanostructure fabrication and characterization using scanning probe-based (STM, AFM). We also are developing numerical simulations of localized electric field and emission current to explore mechanisms and characterize limits to processing techniques. We emphasize novel fabrication processes and characterization of physical, chemical and electronic effects in nanostructures. Critical nanoscale components will be integrated with conventional test structures to allow full electrical accessibility. We also are developing direct-write fabrication processes for nanoscale fabrication using electric fields and the low energy electron flux from an STM to directly induce deposition processes leading to nanostrucutre formation.

Accomplishments

The program has demonstrated significant accomplishments in both experimental and computational investigations of nanostructure fabrication. Many of these accomplishments have been detailed in prior SAND reports. Summaries will be given here, with reference to the detailed reports.

A. Nanometer-Scale Lithography on Si (001) using Adsorbed H as an Atomic Layer Resist

We demonstrate nanometer-scale feature definition in adsorbed hydrogen layers on Si(001) surfaces by exposure to low energy electrons from an STM tip. Feature sizes range from < 5 nm to >40 nm as a function of bias voltage (5 - 30 V) and exposure dose (1 - 10^4 μC/cm). We show that the cross section for electron stimulated desorption of hydrogen has a threshold at

6-8 eV and is nearly constant from 10-30 eV, so that above threshold the feature profiles are a direct reflection of the electron flux profile at the surface. Radial flux distributions are best fit by a simple exponential function, where the decay length is dependent primarily on the tip-sample separation. Low intensity tails at large radius are also observed for high bias emission. Comparison to field emission simulations shows that our tip has an 'effective radius' of approximately 30 nm. Simulations demonstrate that tip geometry and tip-sample separation play the dominant role in defining the electron flux distribution, and that optimum beam diameter at the sample is obtained at small tip-sample separation (low bias) with sharp tips. We show that adsorbed hydrogen is a robust resist that can be used as a mask for selective area deposition of metals by chemical vapor deposition. Fe lines 10 nm wide are deposited by pyrolysis of $Fe(CO)_5$ in areas where H has been desorbed, with minimal nucleation in the H-passivated areas.
For details, see SAND 95-2835J.

B. Selective Area Growth of Metal Nanostructures

Nanometer-scale metal lines are fabricated onto Si(100) substrates by scanning tunneling microscope (STM) based lithography and subsequent chemical vapor deposition (CVD). An STM tip is first used to define areas for metal layer growth by electron stimulated desorption of adsorbed hydrogen. Exposure to $Fe(CO)_5$ at 275°C results in preferential deposition of Fe onto Si dangling bond sites (i.e., depassivated areas defined by the STM tip), while the monohydride resist remains intact in surrounding areas. Fe metal lines with widths ~10nm are constructed using this selective-area, autocatalytic growth technique.
For details see SAND 95-2702J

C. Field Emission Characteristics of the Scanning Tunneling Microscope for Nanolithography

We present a systematic study of the performance of scanning tunneling microscope (STM)-based, low energy electron beam lithography, using simulations of field emission from STM tips, emphasizing realistic conditions of tip geometry and operation. We calculate the potentials and electric field for a hemispherical model emitter in an axially symmetric system. Emission current density at the tip is calculated using the Fowler-Nordheim equation,

and current density at the sample is obtained by calculating trajectories of emitted electrons. We characterize the beam diameter at the sample as a function of emitter radius, tip-sample bias, emission current, resist thickness, and tip work function. The beam diameter is primarily affected by the tip-sample gap, increasing at larger gaps characteristic of high bias and large tip curvature. For optimal tip radius the beam diameter increases linearly with bias from approximately 2 nm at 5 V to 25 nm at 50 V. Beam diameter is nearly independent of emission current over the range 0.05 - 50 nA. Dielectric resist films cause an increase in beam diameter due to increased tip-substrate gap. Beam diameter is very sensitive to tip work function, increasing dramatically for low work function tips. Tips comprised of asperities on flat surfaces produce significantly smaller beams compared to 'standard' tips of the same emitter radius. However, for low bias (< 15 V) beam diameter becomes insensitve to tip geometry. We compare these simulations to selected experimental results to evaluate the limitations to performance and assess the feasibility of routine sub-10 nm structure fabrication using STM-based low energy electron beam lithography.
For details, see SAND 96-0268J.

D. Electric Field Effects on the Nanometer-scale Modification of Au Surfaces

We have investigated contrasting surface modification of Au (111) surfaces in the presence of high electric fields, characteristic of the fields that exist under a scanning probe tip. Dramatic surface distortions are observed when a 200 nm tip, biased at -100 V, is brought toward the Au surface, then retracted. Other experiments maintain a constant high field, and field emission current. STM images taken after each procedure show that high electric field causes step retraction, vacancy island formation, and disappearance of small islands beneath the tip. Very high fields result in unstable bump formation beneath the tip. We have adapted our nanofabrication simulation code to explore effects of electric fields, mechanical forces, and emission current induced heating on surface modification processes in scanning probes. We have shown that for a W tip interacting with a Au surface, surface diffusion of Au atoms in a lateral electric field gradient is responsible for formation of nanometer-scale bumps on the Au surface,in agreement with experiments at high field. This work suggests another practical method for controlled fabrication of nano-scale structures.
For details, see SAND 98-1390C.

Publications Resulting from this LDRD Project

"Selective Area Growth of Metal Nanostructures", D. P. Adams, T. M. Mayer, B. S. Swartzentruber, Appl. Phys. Lett., 68, 2210 (1996).

"Nanometer-scale Lithography on Si(001) using Adsorbed H as an Atomic Layer Resist", D. P. Adams, T. M. Mayer, B. S. Swartzentruber, J. Vac. Sci. Technol. B, 14, 1642 (1996).

"Field Emission Characteristics of the Scanning Tunneling Microscope for Nanolithography", T. M. Mayer, D. P. Adams, B. M. Marder, J. Vac. Sci. Technol. B, 14, 2438 (1996).

"Electric Field Effects on the Nanometer-Level Surface Modificaion of Au(111) Surfaces", H. Cabibil, J. E. Houston, T. M. Mayer, G. E. Franklin, Mat. Res. Soc. Proc., submitted (1998).

"Electric Field Induced Nanostructure Fabrication on Au Surfaces", T. M. Mayer, J. E. Houston, G. E. Franklin, A. A. Erchak, J. Vac. Sci. Technol. B., in preparation.

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