PUB-606

Semiconductor Research Capabilities at the Lawrence Berkeley Laboratory

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Introduction

Lawrence Berkeley Laboratory (LBL) is a multiprogram national laboratory managed by the University of California for the U.S. Department of Energy (DOE). The Laboratory is adjacent to the University of California, Berkeley, and has more than 3000 employees. Its operating budget of about $155 million supports a wide range of research activities. Current programs encompass all the natural sciences, as well as engineering, mathematics, and computer science.

Besides its research role, the Laboratory serves the nation and its scientific and educational communities by developing and operating national experimental facilities for use by qualified investigators. Training future generations of scientists and engineers is another Laboratory role, as is the fostering of productive relationships between LBL research programs and industry.

Semiconductor Research Capabilities

Much of the Laboratory's expertise in semiconductor devices has grown out of long-standing efforts in the development of radiation detectors for research in nuclear and particle physics. Detector systems for high-energy physics research continue to grow in size and complexity, and highly integrated front-end circuitry with data preselection is an essential part of current detector designs. LBL has an active program in integrated circuit (IC) design and advanced silicon device research and development for the U.S. high-energy physics program (Figure 1).

Semiconductor detector research led to the development of growth techniques for ultrapure germanium. This material is used both in large volume radiation detectors and in bolometers for infrared astronomy. Subsequently, the germanium research evolved into the current program in GaAs (gallium arsenide) crystal growth and characterization in the Laboratory's Center for Advanced Materials (CAM), which was formed in October 1983, to provide a structure for more explicitly focusing some of the Laboratory's talents and resources on basic materials research in support of the future needs of U.S. industry.

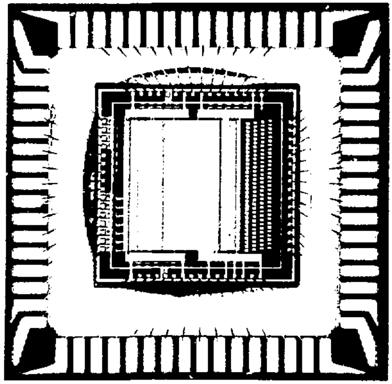

Figure 1. An integrated readout system for high-energy physics detectors. This IC includes 128 channels of low-noise preamplifiers with associated "hit" recognition circuitry and selective data readout. (CBB 868-6470)

Interactions with industrial scientists are a key facet of the overall CAM concept.

Another Laboratory Center, the Center for X-Ray Optics, serves as a focal point for activities aimed at exploiting a broad slice of the electromagnetic spectrum, namely, the soft x-ray and vacuum-ultraviolet regions. LBL scientists have collaborated in the development of an x-ray microscope at the National Synchrotron Light Source, using a zone plate produced jointly with IBM (Figure 2). This development has the capability to probe material surfaces and thin films at resolutions far finer than current (or projected) IC feature sizes.

Other basic and applied research programs at LBL continue to make important contributions to semiconductor materials science, for example, development of powerful models for predicting superconductivity, electronic properties, and crystal structure of materials based only on atomic properties; the mechanism of formation of structural defects associated with ion implantation in

X-ray Lens With 700 Å Outer Zone Width

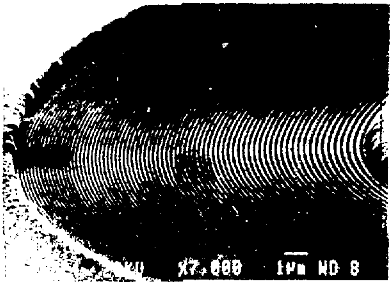

Figure 2. Portion of a zone plate that can be used for focusing soft x-rays. These structures are made as part of a collaborative research program between the Nanolithography Group of IBM's Watson Research Center and LBL's Center for X-Ray Optics. (XBB 860-8114)

Si and GaAs; amorphous layer formation and kinetics of solid-state regrowth of crystalline material; heterojunction solar cell development; the elucidation of properties of the interfaces between metals and compound semiconductors; and radiation damage effects.

National User Facilities

Several of the Laboratory's national user facilities are ideally suited for the study and characterization of semiconductors and related electronic materials, including its heavy-ion accelerators and high-resolution electron microscopes. Laboratory capabilities also include a wide range of structural and electrical characterization facilities and expertise.

The following sections identify examples of research capabilities in advanced materials, semiconductor processing, and packaging techniques. Important large-scale scientific facilities and other instrumentation and expertise at LBL are also identified; key contacts for further information regarding these resources are provided. For further overview information on industry-related semiconductor research at LBL, contact Gerd M. Rosenblatt, Deputy Director, at (415) 486-6606.

Advanced Materials

Theoretical Predictive Capabilities

Solid-state theorists at LBL have developed microscopic theory based on quantum mechanics to explain and predict properties of semiconductor materials, surfaces, and interfaces. Electronic, optical, and structural properties of solids, including new materials not previously synthesized, have been predicted and subsequently confirmed. The motivation for the research is modeling the properties of real materials and predicting the existence of new materials.

Recently, this theory has been used to investigate the possibility of superconductivity in silicon at high pressure. Predictions of the relative stabilities of high-pressure metallic phases of silicon and the occurrence of superconductivity in the simple-hexagonal structure have been experimentally confirmed.

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Crystal Growth

The Laboratory has two special-purpose semiconductor crystal growth facilities. The GaAs laboratory (Figure 3) is equipped with two computer-controlled three-zone multiheating element gradient freeze furnaces with 3-inch and 5-inch diameters, respectively. Single crystals weighing up to 2 kg are routinely grown. Three scientists and a technician work on GaAs crystal growth. The germanium laboratory, staffed by two scientists and a technician, is equipped with two zone refining machines and two Czochralski-type furnaces. Single crystals up to 1.5 kg in

Figure 3. Gallium arsenide laboratory with crystal growth chambers (background and center), fume hoods (right), wafer slicing equipment (lower left), and analytical benches. Satellite analytical laboratories provide for a wide range of spectroscopy capabilities from x-ray to the far infrared, as well as etching and paramagnetic resonance facilities. (CBB 8610-9756)

weight can be grown routinely with electrically active impurity concentrations of $\leqslant 10^{10}cm^{-3}$. Special ultrapure or doped crystals for research and for infrared photoconductors are also grown.

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Characterization Capabilities

A number of characterization techniques are available at LBL for the comprehensive evaluation of as-grown and processed semiconductors. The techniques for structural characterization include:

- Rutherford backscattering (RBS);
- Particle-induced x-ray emission (PIXE);
- Nuclear activation analysis;
- Atomic-resolution scanning transmission electron microscopy (STEM);
- Preferential photoetching;
- X-ray techniques--
  topography, diffraction, photoelectric spectroscopy, fluorescence and absorption fine structure spectroscopy (EXAFS).

Many techniques are also utilized at LBL for semiconductor electronic characterization. These techniques and instrumentation include:

- Semiautomatic system for variable temperature (2–400 K) measurements of the Hall effect and resistivity;
- Deep level transient spectroscopy (with uniaxial stress option) for defect identification;
- Optical system for subband-gap absorption measurements;
- Fourier far-infrared spectrometers;
- Photothermal ionization spectroscopy (PTIS) for ultrapure crystals;
- Electron paramagnetic resonance (EPR) and photo-EPR;
- Raman scattering spectroscopy;
- Positron lifetime measurements.

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Semiconductor Processing Science

Lithography

Synchrotron radiation offers the potential for high-resolution x-ray lithography. LBL scientists have developed the world's brightest x-ray source with the LBL-Exxon wiggler installed at the Stanford Synchrotron Radiation Laboratory (SSRL) (Figure 4). At LBL, the Advanced Light Source (ALS), scheduled for completion in 1992, will have outstanding capabilities for research related to advanced materials and lithography. To highlight one possibility, the development of advanced imaging techniques (by means of projection optics) rather than proximity printing may be the key to lithography for 256-Mbit DRAM chips and beyond. The ALS will provide beams with the high-power, small-beam size, and low-angular divergence needed for research in high-resolution, high-throughput x-ray lithography.

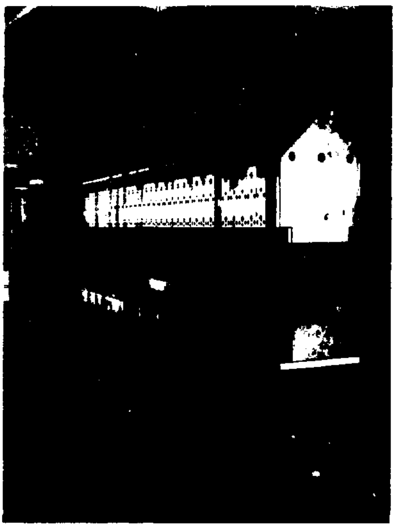

Figure 4. The LBL-Exxon wiggler magnet now installed at the Stanford Synchrotron Radiation Laboratory is the world's brightest source of x-ray beams. Beams at this and other facilities can be used for a wide range of semiconductor materials studies and for the development of advanced lithography techniques. (CBB 833-1798)

The LBL accelerator physics code "ZAP" for optimizing synchrotron and storage ring parameters has been used in the development of several commercial designs for compact "industrial" synchrotron radiation sources.

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Ion Implantation

LBL has expertise, test stands, and fabrication facilities for ion source development. An example is LBL's Metal Vapor Vacuum Arc (MEVVA) ion source (Figure 5). This and several other ion sources can deliver a range of ions at high current with excellent reliability. They highlight the considerable expertise present in the area of source development. These sources have not been applied to semiconductor ion implantation, but these and their developments have potential for the semiconductor industry.

A lathanum hexaboride cathode developed at LBL produces cold electrons as required for the neutralization of insulators during positive-ion implantation. Although the design and development of these cathodes originated from a range of basic research needs, an important application is now linked to IC fabrication.

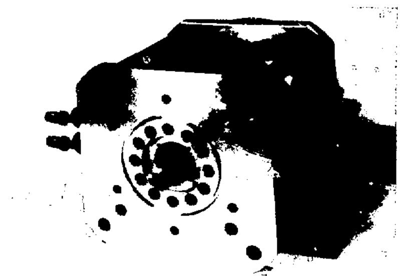

Figure 5. The Metal Vapor Vacuum Arc (MEVVA) ion source can produce a wide range of ions at currents up to 500 mA. Behind the extractor section in the foreground is the plasma arc section (not visible) where intense current concentrations (in excess of 10^{16} A/cm^2) produce a plasma that plumes away from the cathode. (CBB 844-2812)

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Plasma Etching

The plasma research group at LBL has specialized for 15 years in the development and diagnostics of plasma sources and ion beams. Recently, attention has been directed toward applying this technology to improved plasma etchers for semiconductor processing. The group has proposed to develop processes for an advanced high-throughput dry etcher with low radiation damage. The proposal includes experiments comparing ion and reactive species production in low-pressure and microwave plasmas, combined with the development of computer-aided plasma chemistry modeling and diagnostic techniques. Close connections to UC Berkeley groups and semiconductor companies active in this field would greatly facilitate a vigorous collaborative program in this area.

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Semiconductor-Metal Interfaces and Reactions

Metal contacts to semiconductors play a crucial role in the fabrication and electrical characteristics of semiconductor devices. This applies especially to GaAs MESFET technology, and a comprehensive and systematic investigation of the reactions of thin metal films with solid GaAs has been carried out by researchers in CAM. Information on the reaction kinetics and systematics as well as the reacted phase distributions, structure, stoichiometry, morphology, and stability has been obtained for a number of possible contact structures including thin films of Ti, Zr, V, Nb, Cr, Mo, W, Co, Rh, Ir, Ni, Pd, and Pt on (100) GaAs. Correlations between the electrical properties and interface metallurgy for some of the metal/GaAs systems have also been established. A defect model of Schottky barrier formation has been proposed. The model is based on a new class of defects that change their electrical properties depending on the Fermi level position in the band gap. It is shown that pinning of the Fermi energy by the defects explains many of the properties of "as-deposited" and annealed GaAs-metal contacts.

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Packaging Science

Fatigue Resistant Solders

An important failure mechanism in semiconductor devices is thermal fatigue of contacts from periodic heating and cooling, a problem that intensifies with chip circuit density and power dissipation. Research at the Center for Advanced Materials is focusing on two areas: contact design to avoid thermal fatigue and the development of solder contacts that have greater resistance to fatigue. New techniques have been developed for high-resolution examination of solders and wetted solder interfaces. Test structures and machines have been designed that permit straining of the solder interface in pure shear and also impose cyclic shear loads on solder contacts. These studies are revealing solder/copper contact microstructure, metallurgical mechanisms of microstructure development, and mechanical behavior of solder/copper contacts, including their strength, stress relaxation, and fatigue behavior.

Contact: J.W. Morris
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Interfacial Adhesion of Ceramics and Metals

Studies of ceramic-metal bond fracture may lead to improvements in electrical components and assemblies where interfacial failure disrupts electrical continuity, corrosion protection, or other functions. The fracture of ceramic-metal bonds is being studied at LBL in terms of interfacial chemistry, crack tip deformation, and crack interactions with interface morphology and reaction phases. Parallel analyses treat decohesion of deposited and reaction-formed films, respectively, having high tensile and compressive residual stresses. These investigations rely on fracture mechanics measurements, advanced microstructural and interfacial characterization techniques, and indentation methods that induce film delamination. Samples from industrial microfabrication laboratories have been analyzed in the course of this work.

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Properties of Polymer IC Packaging Materials

Expertise in polymer technology is being directed to research on microelectronic industry packaging materials at LBL's Center for Advanced Materials. This work includes: (1) evaluation of thermoelastic stresses in IC packages; (2) determination of dielectric constants and losses of packaging materials; and (3) analysis and control of moisture ingression into packages.

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National User Facilities

National Center for Electron Microscopy

The National Center for Electron Microscopy (NCEM) at LBL provides state-of-the-art facilities for electron-optical characterization of materials and ICs. The resident staff operate and design equipment and software accessible to the national user community. Central to NCEM are two unique high-voltage microscopes, the 1.5-MeV High-Voltage Electron Microscope (HVEM), which is the most powerful electron microscope in the U.S., and the 1-MeV Atomic Resolution Microscope (ARM), which offers the best resolution in the world—better than 1.6 Å (Figure 6). These microscopes are supported by "feeder" microscopes (for screening, preliminary experiments, and complementary microanalysis), preparation facilities, and image analysis facilities. Applications to semiconductors have included studies of bulk semiconductor materials and semiconductor interfaces (Figure 7).

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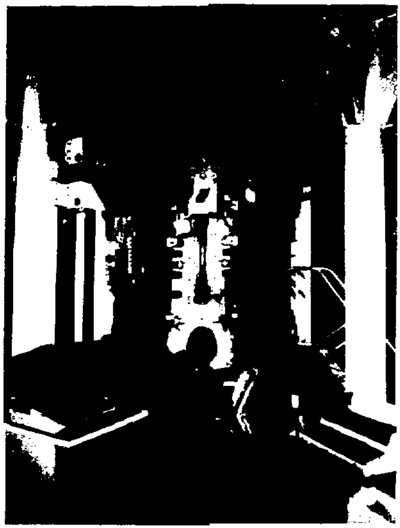

Figure 6. The Atomic Resolution Microscope at the National Center for Electron Microscopy, capable of better than 1.6-Å resolution. The microscope is available to industrial users and has been used for a wide range of semiconductor studies. (CBB 839-8469)

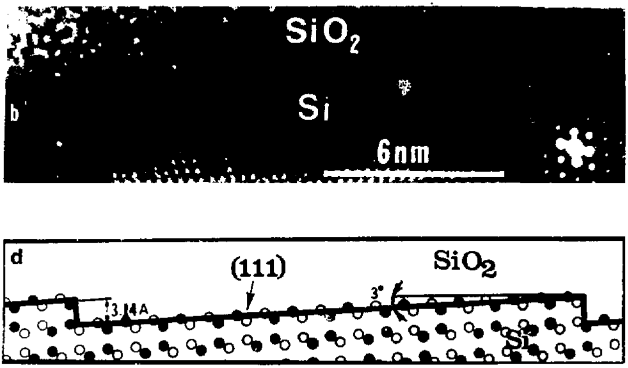

Figure 7. (a) Electron microscope image of the Si-SiO_2 interface. The silicon surface orientation is 3° off the (111) plane. The oxide was thermally grown to 1000 Å thick. (b) Optical diffractogram of the same image. (c) {10$\bar{1}$} diffraction pattern from the specimen imaged in (a). (d) Model of the stepped Si-SiO_2 interface. (XBB 832-1793C & B)

Heavy-Ion Accelerators for Radiation Hardening Studies

Accelerators at LBL have been used in failure analysis and radiation hardening studies by many U.S. electronics companies. The Bevalac, which is capable of accelerating light ions to 2.1 GeV/nucleon and heavier ions through uranium to energies as great as 960 MeV/nucleon, has been used to test integrated circuits intended for space-based applications, in order to test their resistance to cosmic rays, for example. In addition, during the past year, ions from the SuperHILAC were used for deep ion implantation. The 88-Inch Cyclotron was used by more than two dozen companies during the last three years to test the sensitivity of high-speed ICs to radiation-induced effects, such as single-event upset, that would be encountered in a satellite environment in space.

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Advanced Light Source

Enormous potential exists for using synchrotron radiation from bending magnets and insertion devices at electron storage rings. As described in the section on processing science, the Laboratory's next-generation light source, scheduled for completion in 1992, will be an outstanding instrument for research related to advanced materials and lithography.

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