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Sandia Laboratories Technical Capabilities

Electronics

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Sandia Laboratories

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SANDIA LABORATORIES TECHNICAL CAPABILITIES

ELECTRONICS

ABSTRACT

This report characterizes the electronics capabilities at Sandia Laboratories. Selected applications of these capabilities are presented to illustrate the extent to which they can be applied in research and development programs.

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FOREWORD

Sandia Laboratories, a multiprogram laboratory of the Energy Research and Development Administration (ERDA), is located in Albuquerque, New Mexico, and Livermore, California, with a remote testing facility at Tonopah, Nevada. In fulfilling its responsibilities to ERDA in the fields of national security, energy, and other programs, Sandia has acquired extensive capabilities in research, development, testing, and evaluation, and has made numerous contributions in scientific and engineering fields. These technical capabilities are integrated by management for the definition and solution of scientific and engineering problems.

A series of reports has been written describing these capabilities and showing typical applications. The reader will find the capabilities summarized in a separate paper, or may choose any of the 17 separate reports, or, if he wishes a compendium, can find all the reports and the summary compiled in a single publication. Identifying numbers for the entire series are given below.

C. Donald Lundergan, Technical Editor
P. L. Mead, Publication Editor

TECHNICAL CAPABILITIES OF SANDIA LABORATORIES

Summary
(SAND74-0091)

Aerosciences	SAND74-0075	***Instrumentation and Data Systems***	SAND74-0083
Applied Mathematics	SAND74-0079	**Materials and Processes**	SAND74-0078A
Biosciences	SAND74-0076	**Measurement Standards**	SAND74-0077
Computation Systems	SAND74-0080	**Physical Sciences**	SAND74-0074
Design Definition and Fabrication	SAND74-0084	**Safety and Reliability Assurance**	SAND74-0090
Earth Sciences	SAND74-0085	**Systems Analysis**	SAND74-0089
Electronics	SAND74-0086	**Testing**	SAND74-0088
Engineering Analysis	SAND74-0087	**Auxiliary Capabilities** **Environmental Health** ***Information Sciences***	SAND74-0082
Explosives, Electrochemistry, *and Electromechanisms*	*SAND74-0081*		

Compilation of
Sandia Laboratories Technical Capabilities
(SAND74-0092)

ELECTRONICS*

The aim of the electronics activities is to acquire an understanding of the physical properties of elements used in electronic circuits and the effects of fabrication and processing on these properties. Reliability is a basic requirement, and predictable response is necessary under extreme environments such as mechanical shock, intense radiation, and large temperature excursions. Studies of the properties of silicon as influenced by processing variables provide reliable and innovative active elements. Work on new methods of discrete component attachment aids in the miniaturization of hybrid circuits. Substrate and thin-film studies are leading to new electronic materials and providing improved assembly methods.

Vacuum tubes are being designed that allow the rapid transfer of electrical energy and the generation of high-energy neutrons. Pulses of high-current high-voltage electrical charges are generated by the controlled depolarization of ferromagnetic and ferroelectric materials.

Facilities exist for building hybrid microcircuits for evaluating prototype designs. There are large modern clean-room facilities for the fabrication of active semiconductor elements and large-scale integrated circuits. A laboratory is available for fabricating neutron generator tubes and high-energy switching tubes.

Electronics Technical Staff
and Investment in Equipment

	Professional Staff	Investment in Equipment (in $1000)
Active Semiconductors	32	2,500
Hybrid Microcircuits	25	870
Vacuum-Tube Technology	30	4,000
Pulsed High-Energy Technology	65	3,500

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*Compiled October 1975

ACTIVE SEMICONDUCTORS

To assure a reasonable supply of semiconductor components that can meet the size, cost, and environmental constraints of new electronic systems, design techniques, process controls, and procurement methods are developed. Miniaturization is emphasized so that a high level of integration can be accomplished. This in turn leads to reductions in system costs and the significant improvement in reliability attained through redundancy.

Processing

The basic material used in essentially all electronic components of interest is single-crystal silicon. Electrical properties of the crystals are studied as a function of fabrication processes to establish technologies adaptable to optimization of the design of a transistor, diode, or monolithic semiconductor integrated circuit. (Items 1, 2)*

Current Activities

- Stability of high-purity oxide passivation
  - Electrical
  - Temperature
  - Ionizing radiation
- Impurity doping of silicon crystals
  - Thermal diffusion
  - Ion implantation
  - Process modeling
- Mechanical packaging
  - Metalization
  - Wire bonds
  - Beam bonds
  - Die attachments

Design

The relation of electrical characteristics to stresses produced by environments and processing is studied both analytically and experimentally. Analysis is done with computer studies, modeling diffusion profiles, and other parameters before device processing. The development permits considerable customizing of circuits using standard technologies and building blocks. (Item 3)

Current Activities

- Analytical capability
  - One-dimensional device-analysis
  - Logic simulation
  - Computer graphic design
  - Computer analysis of circuits
  - Computer fault analysis
- Special devices
  - Large custom integrated logic systems
  - Micropower transistors
  - Radiation tolerant bipolar devices
  - Standard parts for custom integrated circuits
  - Radiation-tolerant metal-oxide-silicon (MOS) devices
- Quality assurance
  - Interactive computer testing
  - Special procurement procedures
  - Environmental stress testing

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*See Highlights, below.

• • • • • • *HIGHLIGHTS* • • • • • •

Item 1. *Radiation-Tolerant CMOS Development*

More than 150 variations on metal-gate CMOS (complementary-metal-oxide-silicon) processing have been performed to determine the effects of processing variables on CMOS radiation tolerance. Results have allowed development of an optimized radiation-tolerant process by which circuits are made capable of surviving over 10^6 rads Si. The process is compatible with existing commercial CMOS processing and quality controls. Models have been developed which incorporate observed radiation effects in CMOS. The models provide basic physical insight and suggest further improvements in radiation tolerance.

Item 2. *Solar-Cell Development*

A goal of solar-cell development is to optimize the design of single-crystal silicon solar cells for use in multi-sun, high-temperature environments. The cells are to be incorporated in a design that uses solar energy to provide the heating, air conditioning, and other practical needs of a community.

A one-dimensional device-analysis computer code was modified to simulate silicon cells. Beginning with the conventional solar cell, various designs have been successfully analyzed. The physical insight attained has led to modifications in the basic cell, resulting in superior properties at extreme conditions.

Silicon solar cells fabricated in the solid-state device laboratory have verified theoretical studies. Modified designs with optimum top-surface metal, as implied theoretically, have been fabricated and shown to be superior to the conventional cell at both multiple-sun illumination and high temperature.

Item 3. *Large-Scale Integrated Circuit Capability*

A CMOS LSI (large-scale-integration) capability has been developed. Of principal interest is optimization of electronic elements to withstand radiation. The process sequences, including diffusions, oxidation, and anneals that influence both n- and p-channel MOS radiation hardness and threshold voltages have been considered. The work was initially performed on MOS capacitors and subsequently confirmed by the fabrication and testing of CMOS inverter devices. A photolithographic operation was optimized to permit a pattern generation with 5-μm features and less than 4 defects/cm^2. Fabrication also required that wafers maintain a quality level of less than 5 particles (≥ 1 μm)/cm^2. The LSI CMOS capability has been demonstrated by the successful fabrication of functional 210 × 230-mil chips containing 1129 transistors.

HYBRID MICROCIRCUITS

The aim of the study of thin films and hybrid circuit packaging technologies is to establish a scientific foundation for the materials used and for fabrication technology. The study includes identifying and implementing reliable methods of attaching and *interconnecting discrete components.*

Lithography

Chemical and physical processes are established for structuring and defining thin-film materials. Studies assure precision fine-line definition capabilities for film conductors, resistors, and dielectric materials. (Items 1, 2)*

Current Activities

- Computer-aided layout
- Electron-beam lithography
- Ion-beam etching
- Chemical etching
- Lithographic resist systems

Bonding and Interconnection

Techniques are developed for establishing predictable and reliable interconnection systems for hybrid microelectronic circuits. Materials and processing techniques have been developed that provide bonding capability for the diverse electronic component needs of hybrids. (Items 3, 4)

Current Bonding Methods

- *Thermocompression*
- Ultrasonic
- Thermosonic
- Wobble
- Compliant
- Solder

Substrate Studies

Thin films require a dielectric or insulating support to provide a stable carrier for films and components. The aim of substrate studies is to develop, chemically and physically, substrates that are compatible with processing needs and also have the properties of adhesion and heat conduction. (Item 5)

Current Substrate Materials

- Alumina
- Sapphire
- Beryllia
- *Magnetic garnet films*

Film Deposition

Studies of thick and thin-film materials and their interactions are conducted to provide hybrid microcircuit elements that will remain electrically and structurally stable throughout their anticipated life. Environments of interest include shock, vibration, temperature extremes, and electrical noise. (Items 6,7)

Current Activities

Thin Films

- Conductors
  - TiPdAu
  - CrAu
  - Al
- Dielectrics
  - SiO_x
  - Ta_2O_5
- Resistive Films
  - Ta_2N

Thick Films

- Conductors
- Line definition limitations
- Bondability
- Resistor
  - Stability
  - TCR, VCR, noise
  - Static voltage sensitivity

Deposition Methods

- Sputtering
- Evaporation
- Chemical vapor

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*See Highlights, below.

HIGHLIGHTS

Item 1. *Photolithography*

The procedure of optically transferring a pattern to a work piece and the performance of operations upon the work piece controlled by the pattern is called photolithography. By using this technique, and with the aid of photography and chemistry, a pattern can be generated on metal or nonmetal surfaces that serves as a mask to expose or protect the surface from subsequent operations such as chemical and plasma etching, plating, diffusion, epitaxy growth, and abrasion. A wide variety of thin films of either common, precious or rare-earth metals on solid substrates such as glass, ceramic, sapphire, garnet, and metal-metal compounds, as well as on flexible substrates, allows for this type of pattern generation. Patterns may also be defined in nonmetallic materials such as dielectrics. Successive patterns with as many as six levels of thin films have been achieved. Photolithographic processes developed at Sandia provide the only techniques available that will delineate the complex microminiature circuitry demanded by weapon systems, hybrid microcircuits, and special development programs.

Item 2. *Electron Beam Lithography*

Electron beam lithography makes possible improvements in information storage capacity, as well as higher frequency, lower noise, and higher power in magnetic bubble-memory arrays, acoustic surface wave devices, microwave transmitters, charge-coupled devices, and large-capacity metal-oxide-silicon devices. Line widths down to 0.1-1.0 µm can be produced. This method involves use of a short-wavelength ($\lambda \sim 1.7 \times 10^{-5}$ µm) high-energy electron beam (5-30 keV) with a spot size of ~0.05 µm to selectively expose the desired pattern by computer control. A resist-coated substrate is then developed with a solvent solution that selectively dissolves or retains the electron-exposed areas (depending on whether the resist is positive or negative-acting). This provides either channels to the substrate for subsequent metalization, or a mask to protect the underlying metalization from attack during etching.

Item 3. *Bonding*

Thermocompression lead-frame bonding involves applying controlled temperatures and pressures for a predetermined time to normally ductile materials aligned on substrate bonding areas. The basic technology for achieving strong, reliable bonds has been developed. Studies have included the effects of lead thickness and width, electroplating, bonding parameters, [illegible] ation, and substrate support. The introduction of an intermediary to promote deformationless bonds [illegible] thus increase flexure strength while maintaining good strength has been shown to be a viable approach.

Capability exists to perform such interconnection techniques as thermocompression and thermosonic wire and ribbon bonding, ultrasonic wire bonding, and beam lead wobble bonding.

Compliant beam lead bonding has been [illegible] developed and evaluated. This is a method of thermocompression bonding that is relatively insensitive to variations in device beam hardness and thickness. It also permits the beams to be bonded with minimum deformation and stress on the chip-beam connection.

A capability has been developed to evaluate interconnection reliability by using the scanning electron microscope, Auger electron spectroscopy, and several methods of nondestructive and destructive pull testing.

A study has been completed to determine the effects of organic contaminants on solid phase bonding. As seen in Table I, the angstrom thickness of photoresist residue directly relates to the quality of lead frame thermocompression bonding. This information can be used to predict possible bonding problems in production or as a criterion for the amount of cleaning necessary before subsequent bonding should be attempted.

Table I

[illegible]

Condition	Contamination Layer (Å)	Lead Peel Strength[a] Max	Min	Ave	Lead Failure Mode
As [illegible]	2.6	2.61	3.05	2.45	100 [illegible]
[illegible] contaminated with 100 [illegible] resist	10 Å	0.76	[illegible]	0.0	100 [illegible]
Contaminated and exposed to 2? O₃ 27 C [illegible] hrs	6 Å	1.3?	1.90	1.10	100 [illegible]
Contaminated and exposed to 2 O₃ 27 C [illegible] hrs	[illegible]	[illegible]	[illegible]	1.9	100% lead

[a] Units are pounds

HYBRID MICROCIRCUITS

Item 4. *Soldering Components to Hybrid Microcircuits*

A method has been developed, using 50 percent by weight lead indium solder, to attach applique components to thin film gold hybrid microcircuits. Equipment available for solder flow is an infrared soldering system, Browne hydrogen flame resistance loop systems, and various types of hot plates.

Two intermetallic reaction layers have been observed when the interface is aged at elevated temperatures (70-170 C). The layers are shown in Figure 1. The compound nearest Au was established as Au_7In_3 by electron microprobe analysis, while that nearest the solder is a two-phase layer of $AuIn_2$ and Pb. The growth kinetics follows the linear law

$$d - d_0 = \beta t$$

where d is total reaction-layer thickness, d_0 is the original thickness (after soldering), β is a temperature-dependent parameter, and t is aging time. This time dependence has been measured at ten temperatures ranging from 70 to 170°C, which has established growth activation energy as 14000 calories per mole. This was done using the data on β shown in Figure 2. These reaction layers are not brittle and do not lead to significant loss of solder joint strength after extended (1000-hour) aging tests.

Figure 1. Solder-gold reaction showing gold indium intermetallic formation

Item 5. *Substrates*

Substrates are developed to provide a suitable base for depositing thin metallic films used in hybrid microcircuits (HMC). Standard thin-film HMC technology is tailored to be compatible with tape-drawn, as-fired 99.5 percent alumina ceramic as the substrate material. While this very dense alumina exhibits extremely good electrical and mechanical properties, it does require the use of special cutting and drilling techniques. A tape-controlled ytterbium-aluminum-garnet laser is used to cut the alumina to size and holes are made by ultrasonic diamond drilling.

Recent studies have demonstrated that thin-film technology is also compatible with a new generation of ultrafine-grained alumina as well as single-crystal sapphire substrates. Both materials have improved surface finishes, permitting additional circuit miniaturization by allowing the reduction of conductor and resistor geometries.

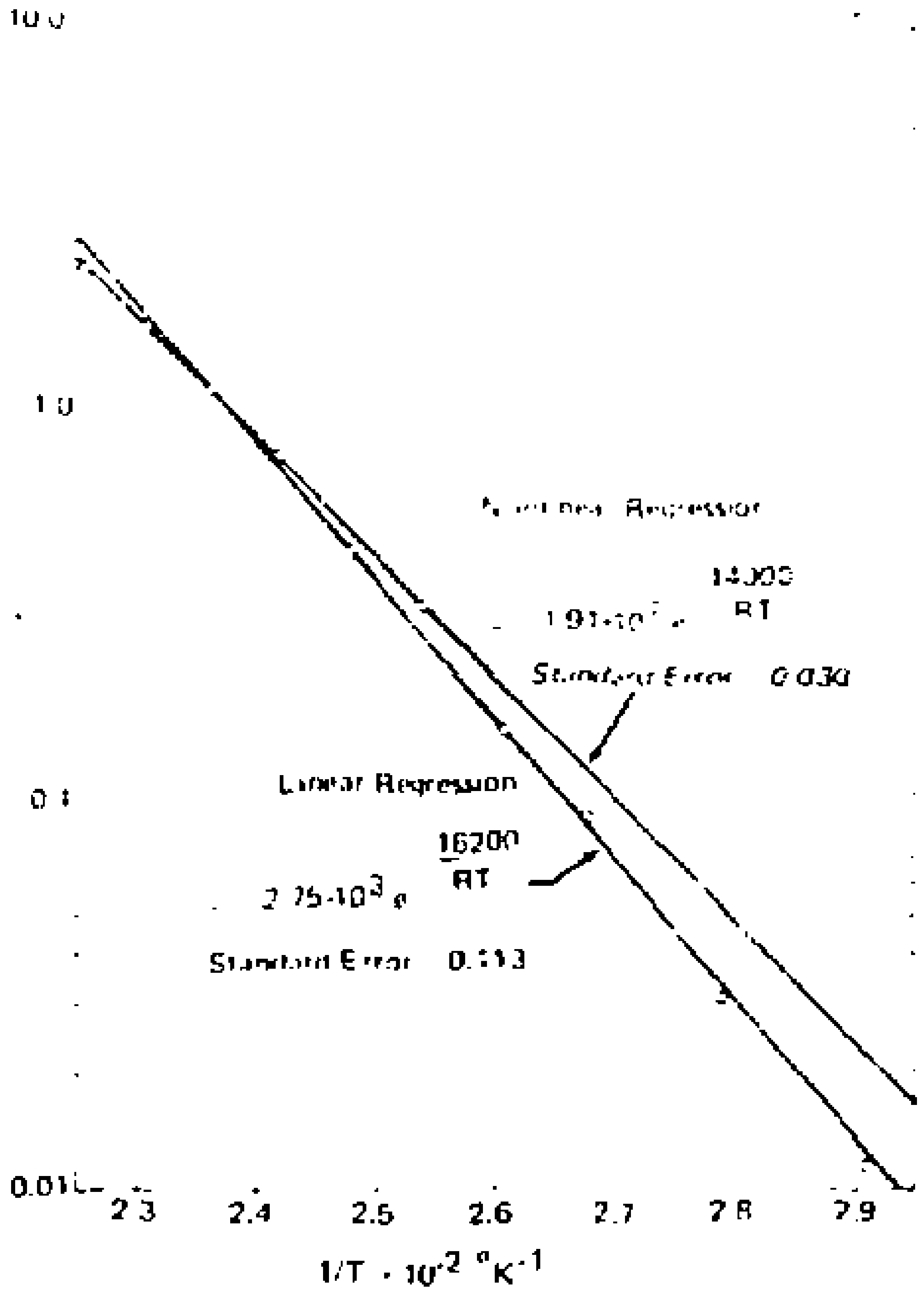

Figure 2. Arrhenius plot showing temperature dependence of β

Item 6. *Sputtering*

One significant application of sputter deposition is the fabrication of thin-film tantalum nitride resistor films for hybrid microcircuits. The objective is to incorporate the resistors as integral elements of the total thin-film network. The films are formed by depositing tantalum in a nitrogen argon atmosphere. Resultant films have a resistivity 30 times greater than that of bulk tantalum, as well as a negative temperature coefficient of resistance. There is also a capability for sputtering tungsten. The technique was used to interconnect thermocouples in a semiconductor thermopile used in development of a small isotopically powered thermoelectric generator.

In another application, where a requirement existed to lay down propagation patterns for magnetic bubble domain memory devices, permalloy films were sputtered.

Item 7. *Thick Films*

While thin films are more generally used in aerospace [illegible] development programs that [illegible] films might offer significant advantages in terms of turnaround and cost. Thick-film technology is a technique for depositing materials on ceramic substrates by precision printing with viscous inks and subsequently firing these materials at very high temperatures to achieve stable electrical and mechanical properties and substrate adhesion. Depending on their composition, these materials may be conductors, resistors, or dielectrics. While these techniques are used to produce hybrid microcircuits, they have recently been used to produce components such as those illustrated in Figure 3.

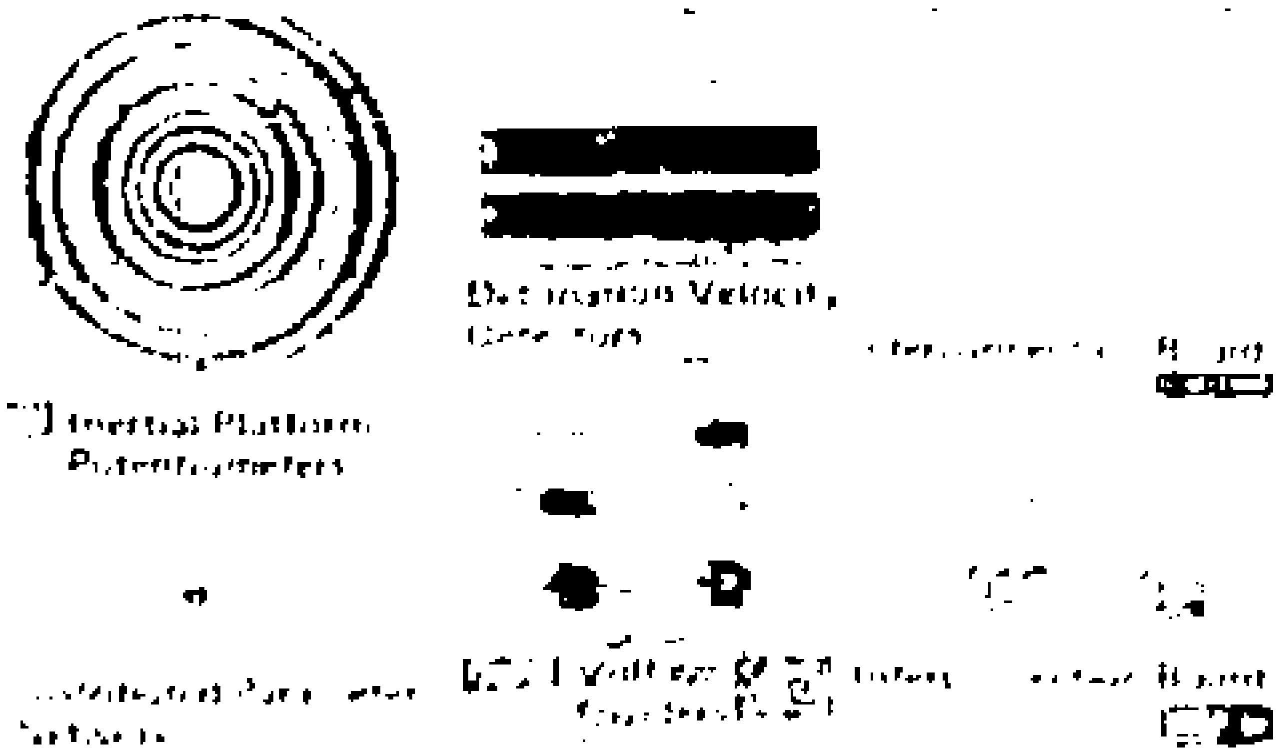

Figure 3. Thick-film applications.

VACUUM TUBES

[illegible] discharges, which [illegible] construction [illegible] Al_2O_3 ceramic [illegible] materials and [illegible]

Neutron Tubes

[illegible] are designed to [illegible] 14 MeV [illegible]. These tubes [illegible] after long periods of storage [illegible] environments [illegible]

[illegible]

- Ion beam optics
- Ion beam target interaction
- High voltage breakdown
- Metal ceramic bonding techniques
- Ion source design
- Hydrogen and helium permeation
- Laminated metals
- Thin film evaporation
- Electrostatic field calculations
- High sensitivity leak detection
- Power supplies
  - Electronic
  - Ferroelectric

Vacuum Tubes for Triggered Electrical Switching

Switching tubes are developed for use in applications where current discharges are to be delivered, on command, to external electrical loads. These devices use a small trigger arc to initiate full vacuum anode-cathode discharge, resulting in a few tens of volts for initiating a 2-10 kV discharge.

[illegible]

- Anode and cathode design
- Arc erosion
- Field emission
- Gold diffusion bonding
- *Ceramic gold brazing*
- Gas effect in discharge characteristics
- Al_2O_3 ceramic parts fabrication
- Gettering surfaces

Vacuum Arc Physics

[illegible] vacuum [illegible] high electric [illegible] tubes use [illegible] for actual [illegible]

[illegible]

- Anode phenomena
  - Anode temperature
  - Plasma temperature
  - Electron density
  - Ion density
  - Plasma constituents
- Cathode phenomena
  - Plasma constituents
  - Spot formation
  - Spot theory
  - Erosion
- Plasma boundary measurements
- Gas effects
- Ion beam mass analysis

Hydrogen and Helium in Metal Films

Hydrogen isotopes, specifically deuterium and tritium, are used in the manufacture of neutron generator tubes. Tritium is a radioactive isotope that decays into helium-3 with a half-life of 12.26 years. The helium-3 remains within the metal lattice although its dimensions are larger than those of tritium, causing concern about lattice strain and subsequent helium release. Thus, it is often necessary to analyze and understand metal hydrides and tritides. Of specific interest is the behavior of significant amounts of helium-3 in the lattice. These films and their contents are analyzed using charged-particle backscattering, gas analysis, ion microprobe, and a wide range of other analytic techniques.

ELECTRONICS

VACUUM TUBES

Current Activities

- Thin-film deposition
- Hydriding kinetics
- Stress levels in thin films
- *Proton backscattering*
- Helium backscattering (Rutherford)
- Surface transport and kinetics
- Oxide surface films

PULSED HIGH ENERGY TECHNOLOGY

This technology is concerned with the generation and use of electrical energy. High-energy electrical pulses are produced by two principal techniques, explosive-to-electric transducers and capacitor discharges. The transducers use various phenomena to produce the electrical pulse, including compressed magnetic fields, ferroelectrics, and ferromagnetics.

Compressed Magnetic Fields

In a compressed-magnetic-field (CMF) generator, explosive energy is converted into electric energy by explosively driving a conducting armature into a magnetic field. Work done in overcoming magnetic forces results in an increase of magnetic energy in the system, which is coupled into electrical loads by solenoidal coils. Magnetic fields in the range of millions of Oersteads and electric currents in excess of 1 million amperes have been generated by this technique. (Item 1)[*]

Current Activities

- Development
  - Solenoidal coils
  - Explosive armatures
  - Explosive lenses
  - Coupled compressed-magnetic-field systems
  - Power supplies
  - Automated digital instrumentation
- Research
  - Magnetohydrodynamic modeling
  - Pure fusion weapon research
  - Armature metallurgy
  - Magnetic-field diffusion
  - Nonlinear circuit modeling

Ferroelectric Transducers

Another method of achieving high-level pulsed high-energy sources is through the use of ferroelectric (FE) materials. Two classes of these materials have been developed for transducer applications: conventional and slim-loop ferroelectrics. Their principal difference is in the shape of their polarization or electrical hysteresis loops. The FE material, an electric analog of a permanent magnet, exhibits permanent polarization or electric displacement when its electric field is zero. Slim-loop FE material, for all practical purposes, has no permanent polarization. Thus, its electric displacement is near zero when the electric field is zero.

In transducer applications FE material is depolarized by an explosively generated shock wave. Depoling during shock-wave transit results in release of the bound polarization charge, causing large transient currents. Slim-loop materials respond similarly except that their polarization charge is not bound but must be supplied by an external source. (Item 2)

Current Activities

- Development
  - Central power supply
  - Neutron-tube power supply
  - Contact fuze
  - CMF injector
  - Explosive lens
  - Automated digital looper
- Research
  - FE material characterization
  - Nonlinear circuit modeling
  - Electric field breakdown physics
  - Phase transition and transition kinetics

Ferromagnetic Transducers

The ferromagnetic transducer is another method used to obtain pulsed high-energy discharges. It derives its output from the shock-wave demagnetization of a magnetic core. It consists of an iron or nickel-iron magnetic core, an excitation winding, an output winding, and an explosive charge. The excitation winding is used to saturate the magnetic field in the core before the explosive is detonated. When the explosive is detonated, the shock wave it generates passes through the core, reducing its magnetization to that of air. The resultant collapse of magnetic flux density generates voltage in the output winding and current flows if an external load is present. The output current capability of a ferromagnetic transducer operating into a low impedance is a few kiloamperes. (Item 3)

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[*] See Highlights, below.

PULSED HIGH ENERGY TECHNOLOGY

Current Activities

Magnetic materials
New explosives
Equivalent circuit modeling
Hydrodynamic modeling
CMF injector
Exploding-bridgewire detonator firing set

Capacitor Discharge Technology

A form investigated for high-energy pulsed discharges is that of capacitor-discharge technology wherein a low voltage is converted to a high voltage (e.g., 28 Vdc to 6 kVdc) in times ranging between 0.1 and 1 second. The high dc voltage charges an energy storage capacitor that is command-switched into an electrical load by a vacuum-tube switch or an explosively driven solid dielectric switch. This technology has been developed for firing a variety of detonator configurations as well as powering spark bits in deep drilling research. The former application emphasizes high reliability and compact designs, and uses radiation-hardened dc-to-dc converters with capacitor charging capability up to 5 watts/in^3 and energy storage capacitors capable of achieving electric-field energy densities of 1.2 joules/in^3. Spark drilling applications emphasize very high energy storage and multiple firings by operating at 60 kV to provide 3-kilojoule sparks at a rate of 120 sparks/second.

Current Activities

Energy storage capacitors
Solid dielectric switches
Vacuum switch tubes
Integrated circuit operational amplifiers, regulators
High-voltage solid-state switches
Hybrid microcircuits dc-to-dc converters
Modular circuit construction
Power amplifiers
High-reliability electronics packaging
Optically coupled dc-to dc converters
Firing subsystems
Spark drilling
Transient pulse instrumentation
Shock, temperature, and radiation-resistant circuits
Missile stage separators
Bolt cutters

• • • • • • *HIGHLIGHTS* • • • • • •

Item 1. *Compressed Magnetic Field Transducer*

A number of small, efficient compressed-magnetic-field generators have been developed (Figure 4). The generator consists of a solenoid coil with an explosively expanding armature located coaxially. After the explosive is detonated from one end, the armature expands, inductance is forcibly decreased, and coil current increased so as to conserve flux linkages. The objective is to achieve a compact pulsed high-energy source.

Item 2. *Central Power Supply*

The central power supply shown in Figure 5 incorporates both ferroelectric and compressed-magnetic-field technology to obtain a firing source for detonators connected to a power source.

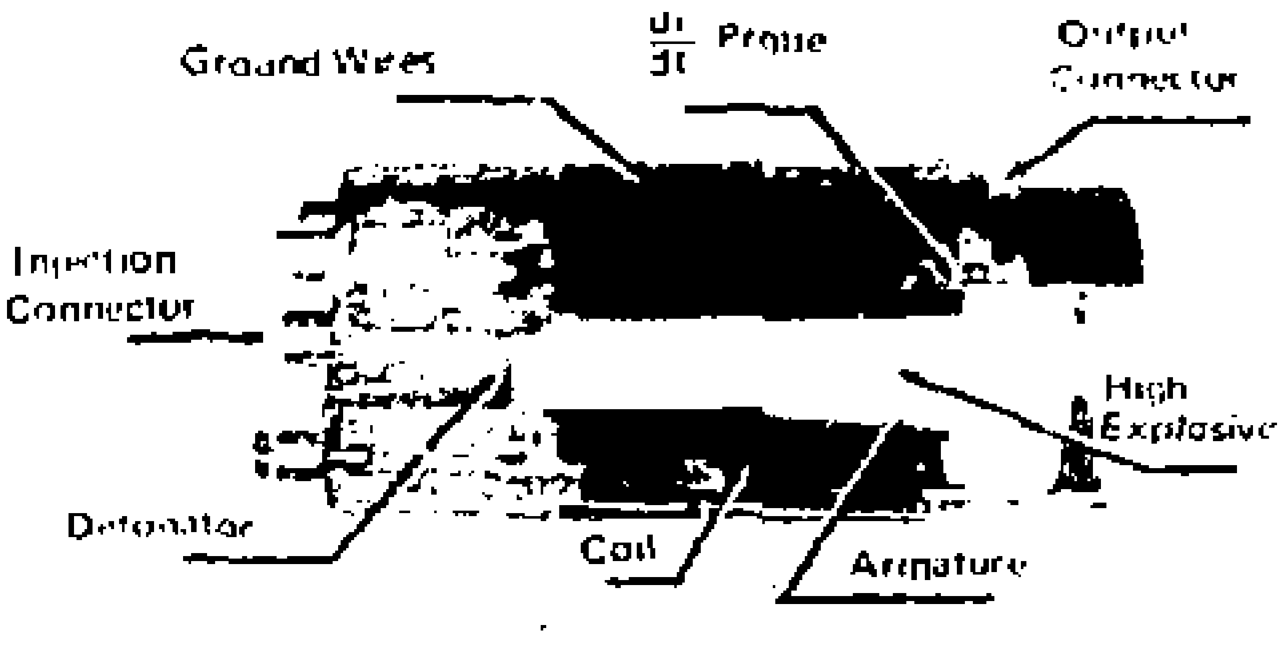

Figure 4. Compressed magnetic field generator

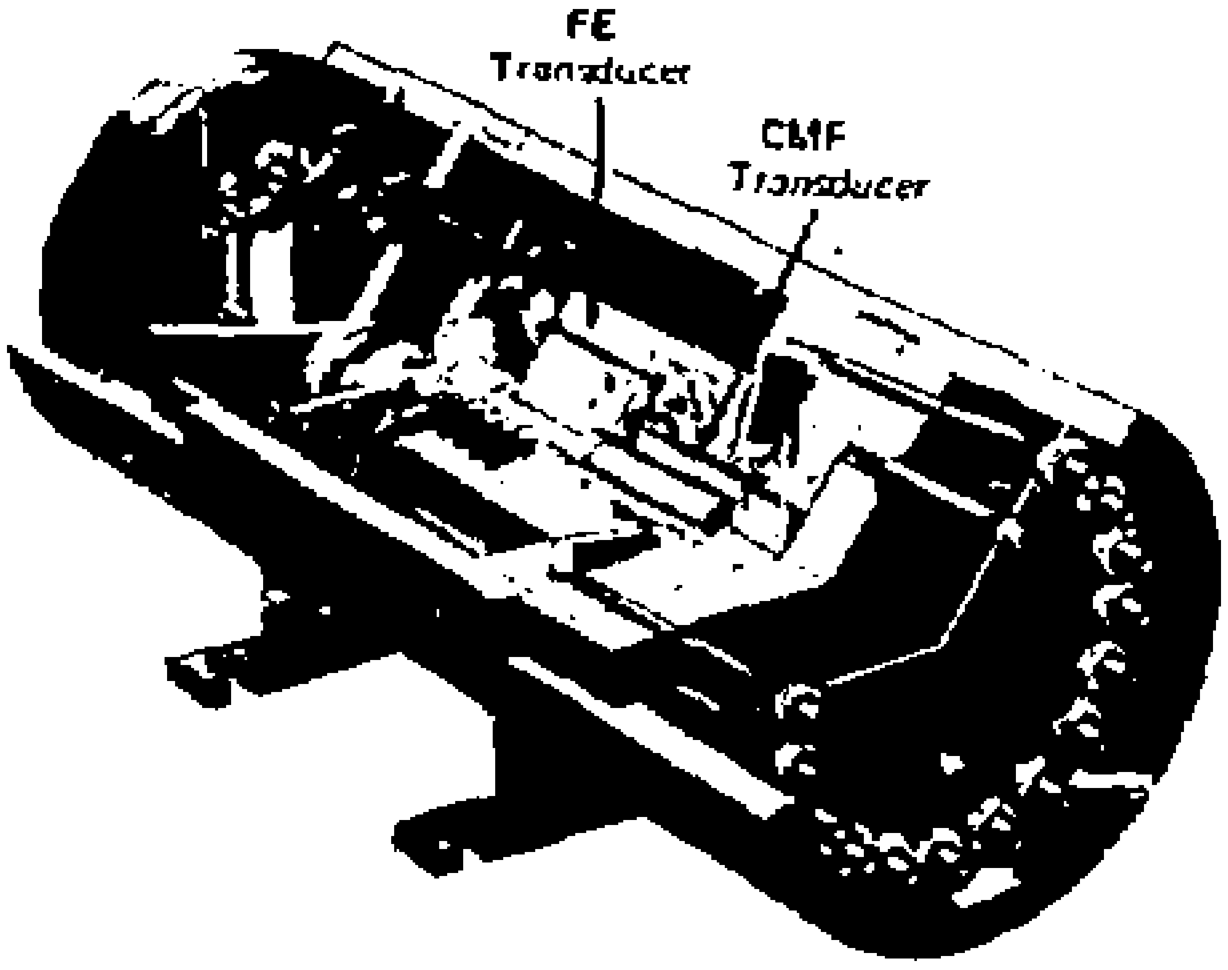

Figure 5. Central power supply

The stress wave from the rupturing glass releases the charge from the FE disks to fire a detonator, which in turn ignites an explosive stick that burns down the axis of the assembly. The radially expanding shock wave from the explosive stick first depolarizes six other FE washers connected in electrical parallel. The current from these washers flows through the coil of a small compressed-magnetic-field transducer, creating an initial magnetic field in the space between the coil and a conducting cylindrical armature inside the coil and concentric with it. The armature is filled with explosive which is part of the axial explosive train. As the explosive burns through the armature, it throws the armature out toward the coil, compressing the magnetic flux, and generating a large current in the coil. The coil is connected to 20 parallel output connectors.

Item 3. *Ferromagnetic Transducer*

A fundamental configuration of ferromagnetic transducers is shown in Figure 6. The magnetic core is nickel-iron and is laminated or tape-wound to prevent parasitic eddy currents. The core is wound with an excitation coil and an output coil. The latter can be matched to various load impedances by varying the number of turns. The explosive train consists of an initiating detonator, a lens, and a driver charge of explosives to actuate the ferromagnetic transducer when the detonator is fired. This detonates the lens, initiating the driving charge in a planar wave. The driving charge sends a pressure wave through one leg of the magnetic core, causing the relative permeability of the magnetic material to be reduced to one. The resultant field collapse generates voltage in the output coil. Transducers of this configuration produce about 1000 amperes.

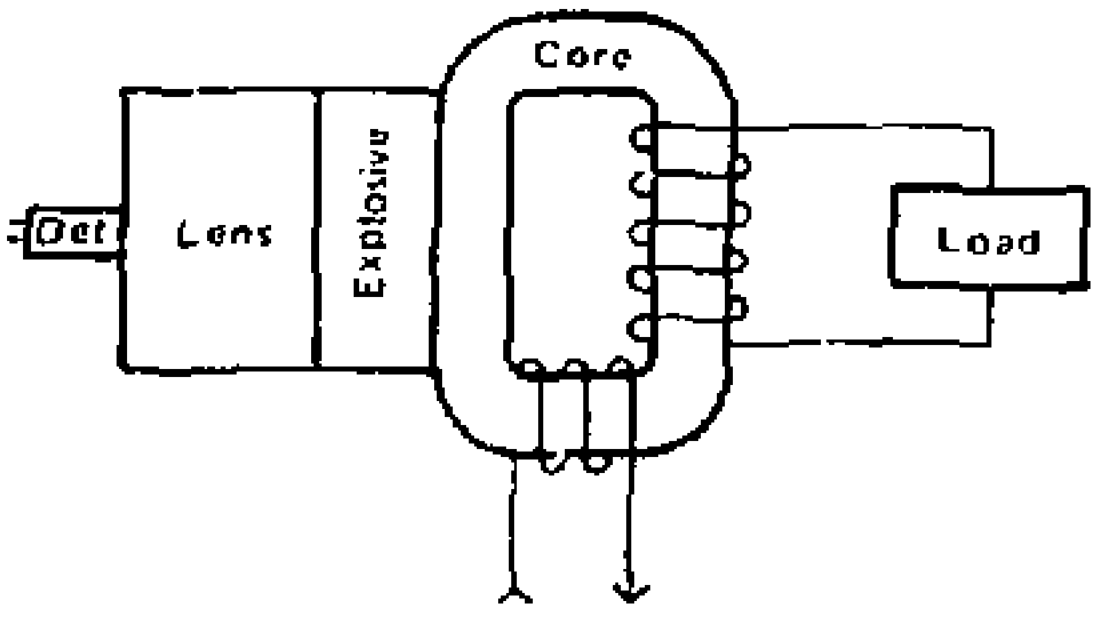

Figure 6. Ferromagnetic transducer configuration