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Electronics Engineering Department Quarterly Report No. 1-1981

Inside: Microstructure fabrication using IC technology.
 High-speed recording of electrical transients.
 The EE Research Division's ion-implantation system.
 High-speed spectroscopy for process control of coal.
 Personal-type microcomputer automatically controls
 video playback facility.

MASTER

April 1, 1981

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Preface

The EE Department Quarterly Report has two purposes—to inform readers of various activities within the Department and to promote the exchange of ideas.

The articles, by design, are brief summaries of EE work. For further details on a subject covered, please contact one of the authors listed at the bottom of the first page of the article. The authors are primarily responsible for the content of the article. Inasmuch as most projects are the result of the cooperative efforts of many individuals, the person you contact may either provide the requested information directly or refer you to the appropriate person to answer your question.

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Integrated-circuit technology is adapted for making precisely shaped parts, with dimensions in the micrometer range

We have adapted methods used in the fabrication of integrated circuits to make ultra-small parts that are virtually impossible to make otherwise. These methods include photolithography, thick photoresist, various kinds of controlled etching, ion milling, and microelectroplating. This adaptation of these methods has been termed "micromachining." We have made arrays of 1- μm pinholes, micro-Fresnel zone plates, membranes down to 1 μm thick, laser target discs up to 10 μm thick, and many other special parts. As we acquire knowledge and skill with these techniques, we are developing an ability to fabricate even more complex microstructures.

The technology of "micromachining," or the use of integrated-circuit techniques to fabricate three-dimensional microstructures, is in its early stage of development, stimulated by the need to mass-produce high-performance, ultra-small sensors, diagnostic devices, and other mechanical parts at low cost. The many innovative procedures used to fabricate integrated circuits (ICs) quite often inspire new ideas on how to fabricate other devices. The literature contains reports of micromachined devices as sensors in medical applications, transducers in automotive engines, and ink jets for computer printers. We have used this technology to make a number of small parts, mostly for diagnostic experiments and for components of laser targets used throughout the Laboratory.

The Electronics Engineering Department operates an IC-fabrication facility where the primary effort is to design and build custom ICs for high-speed transient diagnostic instrumentation. We have been using this facility to fabricate microstructures. Shown in Fig. 1 is such a part, a 12- μm -thick Fresnel zone-plate used in examining laser-induced plasmas. Also shown (for comparison) is a human hair with a diameter of roughly 100 μm .

IC fabrication procedures which are adaptable for micromachining include:

- Photolithography, a process by which selected areas of a surface are covered with an organic film that is not attacked by etchants.
- Orientation- and concentration-dependent etching, the exploitation of differential etch rates to produce a desired shape.
- Microelectroplating, using a mold of the desired shape.

- Reactive-ion etching, i.e., etching conducted in the glow discharge of a gas.

In what follows, we will discuss these techniques and show examples of our work.

Photolithography

Very small images—etching patterns with dimensions of 1 μm or less—can be transferred to a surface via photolithography. In this process, the desired substrate is coated with an organic substance, called a photoresist film, that is sensitive to ultraviolet light but is not attacked by etchants. A special printing system with high-resolution optics is used to expose the photoresist film; the higher the resolution of the optics, the smaller the image that can be formed.

Fig. 1. Typical microstructures: a Fresnel zone-plate (12 μm thick) and a human hair ($\sim 100 \mu\text{m}$ thick). The zone-plate, used in examining laser-induced plasmas, was made with micromachining techniques. These techniques are a valuable spinoff of integrated-circuit technology.

For additional information, contact Dino Ciarlo, (415) 422-8872.

When the exposed photoresist film is developed, the developer can be selected to dissolve either the exposed or the unexposed surfaces. Thus, we can use the same printing template to obtain both positive and negative images.

When the substrate is a silicon wafer, we often want to grow a quartz film on the wafer, because quartz withstands silicon etchants far better than does photoresist. The quartz film is grown thermally. A photoresist image is printed on the quartz. The exposed quartz is then removed with hydrofluoric acid. The remaining quartz acts as a mask for subsequent etching of the underlying silicon.

Orientation-dependent etching

Once a pattern is formed on a quartz-coated single-crystal silicon wafer and the quartz is etched with hydrofluoric acid, we can etch the underlying

silicon material in a number of different ways (Fig. 2). Potassium hydroxide etches the (110) crystal plane several hundred times faster than the (111) plane. Because the (110) crystal planes of single-crystal silicon are perpendicular to the (111) planes, we can use potassium hydroxide to etch into the substrate deep grooves with straight walls (Fig. 2a).

If we need to produce V-grooves (Fig. 2b), we can etch a quartz mask on the (100) silicon wafer plane and again use potassium hydroxide to etch the silicon. The potassium hydroxide etches the (100) crystal plane much faster than the (111) plane. Since the (111) planes form a 54° angle with the (100) planes, grooves with sloping sides (54° from the surface) can be etched. The etching will continue to the point where the two sloping side-walls meet. We use this V-groove technique to make diffraction gratings for surface diffusion studies and microchannels in miniature ink-jet printers.

Fig. 2. Illustration of some effects obtainable with controlled etching of single-crystal silicon. The orientation-dependent etchant potassium hydroxide etches the (110) and (100) crystal planes many times faster than the (111) planes. Since the (110) planes of single-crystal silicon are perpendicular to the (111) planes, we can etch deep, straight-walled grooves (a); and since the (111) planes form a 54° angle with the (100) planes, we can etch steep-sided V-shaped grooves (b). Ethylenediamine pyrocatechol, a concentration-dependent etchant, can be used to form a membrane on the (100) crystalline surface of single-crystal silicon; etching stops abruptly at the boron-doped region, leaving a thin membrane of silicon supported by thicker sections of the silicon wafer (c). To micromachine single-crystal silicon into mandrels for vacuum-evaporated metals films, an isotropic etchant (one that etches all planes of silicon at a constant rate) can be used (d).

Concentration-dependent etching

To fabricate thin membranes in single-crystal silicon (Fig. 2c), we can use a concentration-dependent etchant such as ethylenediamine pyrocatechol. This etchant does not etch single-crystal silicon that has been doped with a p-type dopant, such as boron. To fabricate a membrane, we diffuse boron into one surface, then etch from the other side. The etching stops abruptly at the boron-doped region. We can make membranes as thin as $1\text{ }\mu\text{m}$. Because of the way boron "fits" into the silicon lattice, the membrane is taut and does not sag. It can be positioned very accurately with respect to another part. The masked silicon provides a thick framing support for the membrane.

A thin membrane made by concentration-dependent etching is shown in Fig. 3. The membrane is used as an x-ray transmission window. Membranes like this are also used for pressure-operated valves.

We can also micromachine single-crystal silicon into mandrels for vacuum-evaporated metal films (Fig. 2d). First, we use an isotropic etchant to produce raised, undercut tables underneath masked portions of the silicon. Then a thin metal film is evaporated over the entire surface. When peeled off, the metal separates into pieces with the shapes

Fig. 3. Scanning electron photomicrograph of a membrane made with concentration-dependent etching, and a pinhole in the membrane made with orientation-dependent etching. The pinhole is $260\text{ }\mu\text{m}$ in diameter and the membrane is $25\text{ }\mu\text{m}$ thick.

of the surfaces of the raised tables. Many small metal parts can be made simultaneously by this method. Accordingly, it is attractive for making numbers of very uniform sensors and actuators.

We used isotropic etching to make the silicon mandrel shown in Fig. 4. Hundreds of mandrels like this one, on the same silicon wafer, were used to make gold laser targets of precise thickness ($25\text{ }\mu\text{m}$).¹

Microelectroplating

The micromachining techniques described above are used to produce shapes consistent with the etching characteristics of single-crystal silicon. To make parts with more arbitrary shapes, we use microelectroplating. However, this technique requires a suitable mold around which to electroplate. One way of creating such an electroplating mold is to develop an image of the desired shape in a layer of photoresist film of the desired thickness.

Fig. 4. Scanning electron photomicrograph of a mandrel made with isotropic etching. The inner and outer diameters are 200 and $500\text{ }\mu\text{m}$ and the mandrel is raised $12\text{ }\mu\text{m}$ above the base silicon, which has been etched away. The raised mandrel is actually undercut a few micrometers, a feature that effectively separates metal film deposited on the mandrel from the same metal film deposited on the base silicon, provided the film is no thicker than the depth of etching— $12\text{ }\mu\text{m}$ in this case. Hundreds of mandrels like this one, on the same silicon wafer, were used to make gold laser targets of precise thickness. We have made discs up to $25\text{ }\mu\text{m}$ thick with this method.

Figure 5a shows a scanning electron photomicrograph of a micro-Fresnel zone-plate that was fabricated using photoresist as an electroplating mold. These zone-plates are used to examine laser-produced plasmas.²

The 1- μm -diam pinhole in the gold foil shown in Fig. 5b was fabricated by electroplating gold through a mold of photoresist film. The gold membrane surrounding the pinhole is 2 μm thick and is itself supported by a 10- μm -thick gold foil. This pinhole is but one of an array of 400 identical pinholes spaced 50 μm apart. The array is used in calibrating an x-ray microscope.

The use of photoresist as an electroplating mold is practical for molds that are about as thick as they are wide. However, the process does not work well for molds that are much thicker than they are wide. Long exposure times are required for thicker layers of photoresist, and the exposing light gets diffracted within the film, causing the image to blur.³

Reactive-ion etching

Molds that are much thicker than they are wide are best fabricated by means of a combination of photolithography and reactive-ion etching (Fig. 6).⁴ We start with a glass substrate which has a gold film 100–500 nm thick. We add a thick layer of polymer and a masking layer of evaporated aluminum. We pattern the aluminum with photoresist and an aluminum etch, exposing the polymer. The sample is then placed in a vacuum system, and a small amount of oxygen is admitted. We apply a voltage to generate reactive oxygen ions, which etch the polymer approximately 500 times faster than the aluminum mask. Because reactive-ion etching is an anisotropic procedure, it does not undercut the aluminum mask, and we get straight sidewalls. After the aluminum is removed, we use the remaining polymer pattern as an electroplating mold. Figure 7 shows a scanning electron photomicrograph of a pattern that we reactively ion-etched into an 80- μm -thick polymer film.

Summary

Integrated-circuit fabrication techniques can be used to make extremely small parts that are

Fig. 5. Scanning electron photomicrographs of two structures made by gold microelectroplating a mold of photoresist film. At the top is a 12- μm -thick Fresnel zone-plate. Such zone-plates are used to examine laser-produced plasmas. At the bottom is one pinhole in an array of 400 identical pinholes. The small 1- μm -diameter pinhole is formed in a 2- μm -thick gold membrane, and a 10- μm -thick gold foil supports the thinner membrane. This foil is used to calibrate an x-ray microscope.

almost impossible to manufacture by conventional means. We have successfully micromachined ultra-small diagnostic devices, components for laser targets, and instrument calibration parts. As new methods are developed to micromachine three-dimensional parts (as opposed to the basically two-dimensional features found on integrated circuits), more and more applications for this procedure will be found. We are working on new methods and at the same time applying those already discovered to meet the needs of LLNL's experimental programs.

Fig. 6. Reactive-ion etching is used to fabricate thick straight-walled molds in polymer materials that are then used for microelectroplating. A glass substrate is first coated with gold, covered with polymer, and masked with evaporated aluminum film (a). The aluminum mask is then patterned using a photoresist film and an aluminum etch (b). Next, the polymer is reactively ion-etched in an oxygen plasma (c). Finally, the aluminum mask is removed and the remaining pattern is electroplated with gold (d).

Fig. 7. An 80- μm -thick polymer mold for a zone-plate. The mold was fabricated by reactive-ion etching.

References

1. W. E. Tindall, *Fabrication of Laser Components by Semiconductor Technology*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-82644 (1979).
2. Zone-plate coded imaging was discussed in the January 1978 *Energy and Technology Review*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-52000-78-1, p. 1.
3. D. R. Ciarlo and N. M. Ceglio, "Ultrathick Photoresist Processing," in *Proc. SPIE Semiconductor Microlithography*, March 17-18, 1980, San Jose, CA, Vol. 221, p. 64.
4. N. M. Ceglio, G. F. Stone, and A. M. Hawryluk, "Microstructures for High-Energy X-ray and Particle Imaging Applications," to be published.

LLNL's charge-coupled devices can capture more than 2048 samples at 10^9 samples per second

For the past six years LLNL has been developing and manufacturing special high-speed charge-coupled devices (CCDs) for measuring electrical transients. We have developed high-frequency devices which have higher sample rates (to 10^9 samples/s), smaller electrodes and longer records (to more than 2300 analog samples). Our goal is to determine the practicality of using CCDs to make widely available a high-speed instrument for recording transients.

A new development in solid-state electronics—the charge-coupled device¹ (CCD)—may make possible direct digital recording of very short transients at relatively low cost. In the transient-recording instrument, the CCD samples the high-speed analog waveform and temporarily stores it to allow time for subsequent analog-to-digital (A/D) conversion and output.

For the past six years LLNL has been developing special high-speed CCDs for this application. We have constructed laboratory prototypes that can sample transients at a rate greater than 10^9 analog samples/s. We are currently incorporating these CCDs into prototype transient recorders.

The transient recorder

A typical transient recorder using CCDs is shown in Fig. 1. A transducer converts a transient radiation pulse (such as an x-ray pulse) into an electrical signal. The preamplifier filters and amplifies the signal. Next, the fast sample/hold module—whose function is performed by the CCD—reads sequential samples of the signal and stores these samples in analog form. The CCD then outputs the samples to an A/D converter at approximately 10^{-5} s/sample.

How charge-coupled devices work

Although the CCD shares with the transistor some principles of operation, it uses a new concept to transfer electrical charge in "potential wells" in a

semiconductor. This concept contrasts with that of current modulation, the fundamental operating principle of the transistor.²

A CCD is basically an analog shift-register memory device in which an input voltage (transient electrical signal) is sequentially sampled and converted into a series of electrical charges, called "charge packets," that are proportional to the voltage (Fig. 2). The charge packets are then clocked along the shift register.

The CCD is a metal-oxide-silicon (MOS) structure (Fig. 3) formed on the surface of a monocrystalline silicon substrate. A thin ($0.1\text{ }\mu\text{m}$) layer of silicon dioxide insulator is first grown on the substrate; next, conductive electrodes are deposited. The silicon substrate acts as one set of plates in this series of MOS capacitors, and the deposited electrodes act as the other set of plates. The signal charge is stored on these capacitors in potential wells that can be formed under the electrodes and moved along the structure by sequentially changing the applied voltages. For example, if a positive voltage is applied to one electrode and negative voltages are applied to its two adjacent electrodes, then any free electrons in the semiconductor under these three electrodes would tend to move away from the outer electrodes and collect under the center one. In other words, controlling the voltage on the electrodes changes the potential energy levels of the region immediately under the electrodes. As these potential wells move, they carry with them the mobile charge.

Buried channel versus surface channels

The most common CCDs are surface-channel devices, in which the charge is at the surface of the silicon (at the silicon-insulator interface). These devices are limited in their frequency of operation to about 1 MHz because the charge interacts with

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Fig. 1. Block diagram of the main parts of a modern transient recorder. The key components are the fast sample/hold module and the analog-to-digital (A/D) converter. Sometimes these two are combined into one fast analog-to-digital unit. Using charge-coupled devices (CCDs) for the sample/hold function allows much faster sampling rates than would be possible with the fastest existing analog-to-digital converters.

Fig. 2. Diagram of the sample/hold function of the CCD and photographs of actual input and output signals showing the time-base expansion. The CCD is an analog shift register with an input structure that introduces into the first stage of the shift register a charge proportional to the voltage of the input signal during an appropriate sampling interval. This analog charge packet is then moved along the shift register by the clock waveform. The frequency of the clock determines the speed at which charge packets move along the shift register. Once the shift register is filled, the sampling is stopped and the clock waveform is automatically shifted to a lower frequency to read out the sampled data to the analog-to-digital converter.

Fig. 3. Cross section of part of a four-phase CCD. The CCD consists of a silicon substrate on which is grown a thin insulating layer of silicon dioxide. Conducting electrodes (made of either aluminum or polycrystalline silicon) are deposited on top of the insulating layer to complete the metal-oxide-silicon (MOS) structure. A thin "depletion layer" is formed in the silicon near the interface with the oxide. The only mobile charges here are the electrons in the charge packets. The charge packets are confined and moved by the electronic potential distribution that exists in the depletion layer as a result of the clocking voltages applied to the surface electrodes.

dangling bonds and other charge-trapping states at the interface. To avoid this limitation, designers have devised more complex structures that shape the three-dimensional potential wells so that the charge moves in a buried channel below the surface. Most of the commercial CCD development for memories, imagers, signal processing, etc., has concentrated on the simple surface-channel structure or on a slightly faster "shallow buried-

channel" structure. The fastest commercially available CCDs have a maximum clock frequency of 20 MHz. At LLNL, we have concentrated on high-frequency buried-channel technology. We have clocked CCDs at 250 MHz in the laboratory. The maximum frequency of operation is limited by the state of the art in building fast clocking circuits and not by any fundamental physical limitations of the CCDs.

Increased sampling rate

In 1976, to increase our sampling rate significantly, we applied the concept of "on-chip" demultiplexing of the input signal during sampling. Four CCDs were fabricated side by side on one chip and clocked by a four-phase clock. The input structure was staggered in such a way that the input signal was automatically demultiplexed into the four separate CCD channels. At the end of one clock cycle, the input signal had been sampled four times and stored in four different places, with a known relation between sampling times. The significance of this demultiplexing is that a single CCD chip can operate at a sampling rate four times the highest frequency at which it can be clocked.

This kind of circuit sophistication becomes important because it is the "off-chip" clocking circuitry that limits the speed of operation. One of our goals was to capture 10^9 samples/s by using a four-way demultiplexed 250-MHz clock rate. To achieve this sample rate with 20-MHz commercial CCDs requires 50 CCDs plus an external scheme to sample the analog signal. The delays in routing all these high-frequency signals and clocks to the 50 CCDs would make this method cumbersome and costly at best. Another problem with this scheme is that a CCD, being an analog device, has a certain gain and linearity from input to output. These parameters are very sensitive to variations in processing and materials. With separate channels in separate CCDs, matching the gain and linearity from channel to channel is much more difficult than if all channels are on the same silicon chip.

Even on the same chip, the four CCD channels vary significantly in gain and linearity. Our analysis, and that of others, has shown that the input and output structures are the most sensitive to variations in material and procedures during fabrication. Hence, in our second-generation CCDs, we took special care in designing the input and output to reduce this sensitivity. We made all the input structures as similar as possible, and all the outputs use the same output amplifier. This chip was operated at a maximum clock frequency of 125 MHz—equivalent to a sample rate of 0.5×10^9 samples/s. A dynamic range of greater than 500:1 was attained, which is excellent for such high-speed devices.

Smaller electrodes

Because of the large capacitance of CCD electrodes, one of the most difficult tasks in developing instruments with CCDs is design and fabrication of the high frequency clock. To minimize the difficulty of clocking, we reduced the capacitance of the electrodes making them smaller. With this design, each charge packet in the chip is stored under an electrode whose area is $15 \times 7.5 \mu\text{m}$ —one fourth of the smallest area reported in the open literature for high-speed CCDs.

An important result of this small size is that the potential wells are almost square. To appreciate the significance of this, we must note that the time needed to move a charge packet from one potential well to another is proportional to the square of the distance moved—that is, the distance between the centers of adjacent electrodes. With square potential wells, we have the option of moving the charge at high speed in two axes of the CCD's surface.

Longer records

This ability to move charge rapidly in two directions enabled us to extend to high-speed CCD design yet another design concept, serial-parallel-serial (SPS). The SPS architecture has been used for some time in slower surface-channel technology to build area imagers and digital memories; however, it is new to the high-speed CCD. In the SPS CCD, the signal is sampled, and the charge packets are shifted at high speed along an input register (Fig. 4). After N cycles of the high-speed clock (where N is the number of stages in the serial input register—16 in Fig. 4), the charge is clocked laterally into N separate lateral channels, called parallel storage registers, by pulsing a transfer gate. The first lateral transfer (across the transfer gate) must be fast (one period of the high-frequency clock); after that, in the parallel storage channels, the charge can be moved more slowly ($1/N$ times the high-speed clock frequency). Once all the charge is read into the parallel storage registers, their clock frequency is shifted down to an even lower frequency, and the charge is read out to a single output amplifier.

Fig. 4. Schematic of a serial-parallel-serial CCD design. The electrical signal is sampled and converted to a proportional charge packet by the input stage at the upper left. The charge moves at high speed down a relatively short serial input register (left side), which can be easily clocked at high frequency. Once the serial input register is filled, all its charge packets are transferred laterally into the first stage of the parallel storage registers by pulsing a single transfer gate during one cycle of the high-frequency clock. Since the transfers along the 32 storage stages to the serial output register are made at a lower frequency, the performance specifications of the clocking circuits for these transfers can be significantly lowered.

The two primary advantages of this design are that only a small portion of the chip (the serial input register) must be clocked at the very high frequency and that the high-frequency clock need not be switched from one frequency to another. Therefore, the performance requirements of the high-frequency clocking circuits can be greatly simplified. We are hoping that with this SPS structure we will no longer be limited by the clocking electronics and will be able to operate the CCDs at their inherent maximum frequency. Our calculations have shown that a charge packet should be able to traverse the $7.5\text{-}\mu\text{m}$ gate in less than 10^{-9}s . If this time is half the period of a square-wave clocking signal, the maximum frequency of the clock is 500 MHz. This frequency corresponds to a sample rate of 2×10^9 samples/s when demultiplexed four ways.

Current work

We are currently manufacturing two CCD designs for applications in two different transient recorders. One is a five-channel linear chip. It uses no on-chip demultiplexing of the signal, so that each channel may be used individually if desired. We are now supplying these chips to Los Alamos National Laboratory (LANL) under a joint agreement wherein we are to supply the CCDs and they are to build, for both laboratories, a prototype of a transient-recording instrument. These linear CCDs can store 640 samples before switching down in frequency to read out. The high-frequency clock capacitance of this chip is 40 pF. The second design is a four way demultiplexed SPS chip. This chip can store more than 2300 samples before readout. In spite of permitting almost four times as many

samples in the record, the high-frequency clock has a capacitance of only 20 pF, which illustrates the advantages of this new design. We are in the process of building a prototype of a transient recorder based on this SPS CCD design.³

Considerable laboratory testing has been done on both of these designs. We have operated both chips at clock frequencies greater than necessary for the goal of 10^9 samples/s when the signal is demultiplexed into the separate CCD channels in the transient recorders. Both chips show no indication of reaching their maximum operating frequency. We are still limited in the clocking speed by our clocking circuitry. Clocking of the SPS design at higher frequency should be possible with state-of-the-art clocking circuitry.

Conclusions

In the past six years we have seen a steady improvement in performance of CCD chips built at LLNL. We have pushed the sample rate from 10^8 to over 10^9 samples/s, while increasing the signal-to-noise ratio to over 500:1. With the linear design, we have made modest increases in record length (sample per chip) by reducing the electrode dimensions to maintain low capacitive loading of the clock drivers. The development of the new SPS design, however, allows us to record many more samples without the need for a new development in clock-circuit technology. Successful exploitation of these devices in instruments should make transient

recording an inexpensive, and therefore more useful, diagnostic technique.

Notes

1. The charge-coupled device was first described by Bell Telephone Laboratories (see W. S. Boyle and G. E. Smith, "Charge Coupled Semiconducotr Devices," Bell System Technical Journal, **49**, April 1970, p. 587).
2. For a good survey of CCDs, see Gilbert F. Amelio, "Charge-Coupled Devices," *Scientific American*, February 1974, p. 22.
3. A Transient recorder using the four-way demultiplexed SPS design is mentioned briefly in the *Energy and Technology Review*, January 1979, Lawrence Livermore National Laboratory, Livermore, CA, (UCRL-52000-79-1), p. 24.

For further reading

Joseph W. Balch and Charles F. McConaghy, *A CCD Intergrated Circuit for Transient Recorders*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-78360 (1976).

Michael D. Pocha, Joseph W. Balch, and Chares F. McConaghy, *Two New CCD Architectures for High Speed Transient Recording*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-81791 (1978).

Details of the EE Research Division's ion-implantation system, which precisely implants any ion (up to osmium)

The Engineering Research Division's ion implantation system is a 200-keV, intermediate current (100 μ A), hot-filament, post-analysis system. The mass $\times$ energy product is 38. Therefore, the heaviest ion that can be implanted at 200 keV is $38/0.2 = 190$ amu (osmium). Typical scanned ion beam currents are 75 μ A for boron and 150 μ A for arsenic. Gaseous, liquid, or solid sources can be used.

This method of implantation is greatly superior to high-temperature thermal diffusion in controllability and precision. The use of a hot-filament source in this machine allows us to widen the choice of implantable ions, making possible the creation of new and exotic solid-state devices and further reducing dependence on thermal diffusion methods.

During the fabrication of solid-state devices, ions are introduced into a host material, usually a semiconductor wafer, in order to control its resistivity. Thermal diffusion is a common method to introduce ions. Another method is bombardment of the host material with ions accelerated to a high energy—a procedure called ion implantation. Ion implantation has three advantages over thermal diffusion: 1) the base material does not have to go through high-temperature stress, 2) the number of ions implanted can be closely controlled, and 3) the site of implantation can be closely controlled.

System configuration

The Engineering Research Division's ion implantation system was made by a commercial firm from specifications (LES 22062). The system is a post-analysis machine, so called because the ions are accelerated to a high energy before being analyzed in a mass spectrometer to select the ion to be implanted. The ion source is a hot-filament type. Vapors of the atoms to be implanted are introduced into the ion source region from gaseous, liquid, or solid sources. Once in the source region, the vapors are ionized by an electron beam from the hot filament. The ions are then extracted by the high-voltage accelerator.

After the high-energy ion beam is selected by the mass spectrometer, it is scanned across the wafer. A current integrator measures the total number of ions incident on the wafer. To exclude

any neutral atoms and assure an accurate count of the implanted ions, the ion beam is electrostatically deflected through a 7° angle just before striking the wafer. The system is easy to use, being entirely controlled from the console. The gas pressure, beam focus, voltage, and selection of ion to be implanted are all adjustable by console controls.

System capability

Since the system accepts gas, liquid, or solid source material, it can implant almost any element. There is a limit, however, to the highest energy to which a heavy ion can be accelerated, because the selection magnet in the mass spectrometer has a mass-time energy product of 38. The heaviest ion that can be accelerated and selected at 200 keV is $38/0.2 = 190$ amu (osmium). Heavier ions can be implanted, but not at 200 keV, because they are too heavy for the magnet to turn them into the beam line.

Table 1 lists the ions that have been implanted with the EE system. All but the silicon ion were used for the fabrication of silicon integrated circuits. The silicon-ion implant was used to fabricate gallium arsenide integrated circuits. Typical beam currents that can be achieved at both high and low energies are also given. For the silicon ion, the beam currents for all three of the isotopes are given in Table 1. When silicon is implanted, the isotope with an atomic weight of 30 (Si_{30}^+) is usually selected instead of the more common (Si_{28}^+) so that molecular nitrogen, which has a molecular weight of 28 amu, can be excluded.

The beam is electrostatically scanned over a 5.39×5.39 cm area. The lowest density that can be

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TABLE 1. Typical scanned ion beam currents (μA) achieved with the EE Research Division's ion-implantation system for the various ions implanted to date.

Ion	Source	Beam energy	
		40 keV	200 keV
B_{11}^+	BF_3	2	75
P_{31}^+	PF_5	20	181
As_{75}^+	AsF_5	40	150
$\text{O}_{16(2)}^+$	O_2	Not used	150
Si_{28}^+	SiF_4	0.63	2.1
Si_{29}^+	SiF_4	0.06	0.2
Si_{30}^+	SiF_4	0.03	0.1

achieved with a short (5 s) duration of the weakest (15 nA) beam current is calculated as follows:

$$\begin{aligned}
 \text{Dosage (ions/cm}^2\text{)} &= \frac{(\text{current} \times \text{time})}{(\text{coulombs/ion}) \times (\text{area})} \\
 &= \frac{(1.5 \times 10^{-8}) \times (5)}{(1.6 \times 10^{-19}) \times (5.39^2)} \\
 &= 1.6 \times 10^{10} \text{ ions/cm}^2
 \end{aligned}$$

At the other extreme, by the same equation, the highest ion density achievable with a long (8 hr) duration of the strongest (150 μA) beam current is 9.3×10^{17} ions/cm².

In general, the depth to which an ion is implanted into a base material increases with ion energy and decreases with atomic mass of both the implanted ion and base material. Implant depths are usually less than 1 μm . The implanted layer always undergoes heavy damage, which must be repaired by annealing.

A 200-keV ion-implantation system can be made to behave like a 400-keV machine by selecting ions that are doubly charged, for example, B_{11}^{++} . However, the beam current for doubly-ionized atoms is generally lower than the beam current for the same singly-ionized atoms.

For systems with hot-filament sources, such as the one we are discussing here, the beam current can be substantially increased by selecting molecular ions, such as BF_2^+ , PF_2^+ . However, because of their greater mass, implantation of these ions is very shallow.

Figure 1 shows an example of a spectrum taken before a silicon ion implant. The source was SiF_4 gas, but the source chamber contained residual gases from previous implants, as the figure reveals. The presence of "impurities" is of no adverse consequence in practice, since the desired ion is precisely selected. In fact, the known impurities are of great help in positively identifying the spectrum. The spectrum shown in Fig. 1 derives from the ion beam current obtained with different settings of the selection magnet. By knowing the atomic weights of the various gases in the system, it is rather easy to identify the peaks in the spectrum. The spectrum shows that the system can resolve and separate all three isotopes of silicon. Once the appropriate ion current peak is identified, the system is tuned to this peak and the implant proceeds. One could, in this case, for example, implant the isotope Si_{29} by setting magnet current to 49 A. Measurements of the implant uniformity over a 5.39×5.39 cm area have a standard deviation of $\pm 0.5\%$.

The target chamber is now arranged so that it will accept four 3-in.-diameter wafers or six 2-in.-diameter wafers. The implant angle can be varied from 0° (normal incident) to 16°. We have another chamber insert that allows us to heat or cool the sample during the implant. With some modifications, the target chamber could take samples of other sizes and shapes.

The following list of examples of successful implants gives some idea of the versatility of the system:

- Phosphorous, arsenic, and boron implants for silicon charge coupled devices used in a transient digitizer.
- Boron implants for threshold voltage adjustments in silicon MOS custom integrated circuits.
- Phosphorous implants for ohmic contacts to solid-state devices.
- Oxygen implants into silicon for enhancement of minority-carrier lifetime.
- Silicon implants for gallium arsenide integrated circuits.

Fig. 1. Ion spectrum. This record is obtained by measuring the ion beam current as a function of magnet current.

This system could be used in any experiment where a specific ion is to be implanted at a specific density and depth. For example, experiments on ion-implantation to control corrosion or radiation damage have now become more feasible. In the future, we will be able to extend the range of implantable ions, making possible new solid-state devices.

Summary

The Engineering Research Division's ion implantation system is being used to fabricate silicon

and gallium arsenide integrated circuits and other solid-state devices. Ion densities from 10^{10} to 10^{16} ions/cm² are routinely implanted at energies from 35 to 200 keV. At 200 keV the ions penetrate the base material up to about 1 μm , depending on the atomic mass of the base material and the implanted ion. To date, only those ions suitable for solid-state device fabrication have been implanted, but the ion source is versatile and the system can be used to implant many other ions. This system could be used in any experiment where a specific ion is to be implanted to a closely controlled density.

On-line neutron activation analysis of coal with high-speed spectroscopy

We have developed a new spectrometer that makes possible for the first time the on-line analysis of coal to be burned in a power-generating plant. Gamma rays from the irradiated coal are detected by a Ge(Li) detector. Very high throughput is achieved, with rates up to 150 000 counts per second. The innovation most responsible for the achievement of such a high throughput is the use of time-variant filtering.

Effective on-line process control of coal has not previously been developed, because the analysis could not be done rapidly enough. Traditionally, the lack of means of rapid coal assaying has precluded on-line process control for pollution or quality control.

We embarked on the task of developing a high-rate spectroscopic analysis system for coal.¹ Our system uses a Ge(Li) coaxial detector for neutron capture with prompt neutron activation of irradiated coal samples. We encountered a fundamental problem at the outset—how to meet the conflicting requirements of good resolution and high counting rate. High counting rates are necessary to keep measurement times short enough, at a given level of statistical precision, to

allow process control. The large dynamic range of the spectrum (1 to 10 MeV) means that the gamma peaks span only a few channels of the spectrograph. We solved this fundamental problem with the use of a time-variant filter.

Filters for spectroscopy

The conventional spectroscopy system uses time-invariant Gaussian filters. These are lumped-parameter active or passive filters for optimizing the signal-to-noise ratio. The filter parameters or weighting function produce a quasi-Gaussian waveform that is, in this application, about 20 μ s wide at the baseline.

Many random pulses can arrive in a 20- μ s interval. Closely spaced pulses will distort the baseline and therefore degrade the pulse-height

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Fig. 1. Block diagram of the time-variant system.

(energy) resolution. These "piled-up" pulses can be discriminated and rejected—the traditional solution. However, this traditional solution improves precision and resolution by sacrificing throughput (in many cases up to 80 or 90%). Such an impairment of throughput constitutes an effective slowing of the system, to the point where it becomes unsuitable for process control.

Throughput can be greatly improved with a trapezoidal filter. This filter produces pulses one tenth as long as those of a conventional filter with equivalent noise performance. The trapezoidal filter has a flat-topped waveform that resembles half a trapezoid. This shape is difficult if not impossible to produce with a time-invariant filter because it would require an infinite number of poles. Therefore, we designed the desired trapezoidal waveform by using the time-variant type of filter.

Time-variant filter

In recent years, several papers on time-variant filters for high-rate spectroscopy have been published.²⁻⁴ This type of filter comprises a time-invariant Gaussian prefilter and a time-variant gated integrator. The trapezoidal shape is realized by convoluting the Gaussian function with the rectangular function. This type of filter has two variable parameters: the shape and the width of the filter weighting function. The width of the flat top of the trapezoid depends on the width of the Gaussian prefilter and the width of the rectangular function.

Advantages of time-variant shaping

The greatly reduced width of the trapezoidal waveform allows high count rates with decreased rejection for pulse pile-up.

The flat top of the time-variant filter is also very important. It is this feature that gives optimum performance for slow charge collection of high-energy events in the system. Relatively long collection times result from defect traps and long transit time within the detector. Variations of several hundred nanoseconds have been observed in this system. In a time-variant system, the slow events must be rejected to enhance resolution, and

this may account for rejection of 30% or more of total events. The flat top of the waveform allows these slow events to be equally weighted with the normal events.

In summary therefore, the width and shape of the trapezoidal weighting function of this time-variant filter improves throughput by reducing two kinds of rejection of pulses—rejection for being too closely spaced and rejection because of long collection time.

The advantages of this system are not realized without trade-offs. The time-variant system is complex and requires careful adjustment and setup procedures. The complexity also adds somewhat to the expense of such a system. The time-variant approach is justifiable only when designing for a dedicated system such as this, where throughput, resolution, and peak shape are all of prime importance.

The system and how it works

The system we have developed includes an intense ²⁵²Cf neutron source for activating the coal, a high-rate Ge(Li) gamma ray detector and a microprocessor-controlled multichannel analyzer. Special programs convert raw data to elemental abundances.

Figure 1 is a block diagram of the system. A 20% Ge(Li) ORTEC detector is coupled to the preamplifier, which has been modified for high count rates. An RLC amplifier⁶⁻⁸ contains the prefilter and also provides pole-zero cancellation and baseline stabilization. Excellent baseline recovery is accomplished by Gaussian filter stages which are independent of the gain-determining elements. Dc drift, including changes in detector current due to count rate and time, is compensated by the baseline stabilization circuit. This stabilizer is a gated "wrap around" restorer with a large gain bandwidth to maintain the baseline when count rates are high. The stabilizer is also responsible for excellent long-term stability. The prefilter time constant is 0.25 μ s; it produces an output pulse with superb baseline recovery at high rates. Figure 2 shows the prefilter output for 125 000 counts per second.

The output of the prefilter is delayed 0.5 μ s and then fed to the gated integrator. This delay

Fig. 2. RLC amplifier output pulses (tracings of oscilloscope recordings).

Fig. 3. Gated integrator output pulses (tracings of oscilloscope recordings).

allows the timing circuitry to establish the proper time for strobing the gated integrator.

The proper "zero" time of the event is determined by the timing filter and constant fraction discriminator. The delay and gate generator provide the rectangular pulse of correct delay and width for the gated integrator.

The trapezoidal output pulses from the gated integrator (see Fig. 3) are fed to the analog-to-digital converter of the multichannel analyzer.

System performance

In this system, energy resolution and peak symmetry are greatly improved over those of a con-

ventional time-invariant system. At rates of 150 000 counts per second excellent energy resolution can be obtained. The resolution for H_2 (2.223 MeV) is 4.0 keV FWHM, with peak symmetry of less than 1.9 (FWTM/FWHM). The resolution at 7.6 MeV is 6.5 keV FWHM, for 150 000 counts per second. A conventional amplifier operating at 2/3 this rate with 1 μ s shaping degrades the pulse-height spectra about 40%.

Figure 4 shows a portion of the energy spectrum for widely different samples of coal. The capture gamma spectra were accumulated at detector rates of 150 000 counts per second.

The performance of the system is impressive, and we are proceeding with plans to install the analyzer this year in a TVA coal-fired power plant.

Fig. 4. A portion of the energy spectrum for widely different samples of coal. A—high-sulfur eastern bituminous (East Ohio); B—low-sulfur eastern bituminous (East Kentucky); C—low-sulfur western sub-bituminous (Decker).

References

1. T. Gozani, D. R. Brown and H. Bozorgamesh, in *Proc. of Coal Technology-Europe, Köln, 1981* (Waalhaxen, ZZ44, 3088HJ, Rotterdam, 1981), 2, pp. 355-379.
2. V. Radeka, *IEEE Trans. Nucl. Sci.* **NS-19**, 412 (1972).
3. N. Karlova, *IEEE Trans. Nucl. Sci.* **NS-22** (1975).
4. T. V. Blalock and C. H. Nowlin, *Rev. Sci. Instrum.*, **40** (8), (1969).
5. E. Sakai, *IEEE Trans. Nucl. Sci.* **NS-15** (3), 310 (1968).
6. J. L. Blankenship and C. H. Nowlin, *IEEE Trans. Nucl. Sci.* **NS-13** (3), 495 (1966).
7. C. H. Nowlin, *IEEE Trans. Nucl. Sci.* **NS-17** (1), 226 (1970).
8. D. R. Dunn, R. C. Kaifer, and J. H. McQuaid, *IEEE Trans. Nucl. Sci.* **NS-19**, 461 (1972).

Personal microcomputer automatically controls video playback facility

Our growing video playback facility became difficult to operate when heavier operating schedules overloaded the operator. As a result, minor distractions occasionally led to some missed recordings and playbacks. We solved this problem by installing an inexpensive, yet interactive, controller to watch the clock for us. The controller, a personal microcomputer, plays and records videotapes at the scheduled times, while the operator does other work.

Background of facility

The Laboratory uses many methods to provide continuing education for its scientific, engineering, and technical staff: (1) Microwave connections provide live classes instantly from the University of California's Berkeley and Davis campuses, and Stanford University. (2) A large videotape facility provides delayed presentations of university and internal classes to accommodate the schedules of our employees. (3) The facility also plays, on demand, canned courses from our comprehensive library.

Starting modestly with a few carrels in 1970, the video play and record facility had evolved by

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early 1980 into an 18-input/20-output, manually operated complex. (See Fig. 1.) Multiple recordings and playbacks—that started or ended on the hour, half hour, quarter hour, ten-after-the-hour, and other odd times—created a situation where the time pressure and the potential for error were great.

Design objective

In solving this problem, our objective was clear: to take the clock-watching burden away from the playback-center operator. We wanted a system that would start a dozen video player/recorders at specified times and simultaneously switch the player/recorders to the proper input or output channels. Thus, we defined the functions needed: a

Fig. 1. These two pictures show the contrast between the old manual system and the new automated approach. Before, the operator had to check her watch and wait to turn on a recorder. Now, after loading the recorders, she rests a moment at the microcomputer console and lets it watch the clock.

day and time-of-day clock, a remote-control switcher, a fan-out to the remote-control input of many video-tape recorders (VTRs), and a system for storing and manipulating schedules that the operator could manage easily.

System description

Three major components comprise our system: a microcomputer, a video switcher, and several video-tape recorders (Fig. 2). They are tied together with an IEEE-488 general purpose interface bus (GPIB).

Microcomputer

The microcomputer is the controller of the system, and contains the interactive program which we wrote. The program detects, decides, and commands in accordance with the information dynamically given by the operator. To help the microcomputer operate the video switcher and VTRs, we designed two separate interfaces for translating computer commands: one for commands for switcher actions, and the other for commands for VTR actions. A separate subprogram and a separate interface scheme were required for each interface.

We chose the PET microcomputer, (Commodore Business Machines), because it is reliable and it supports the GPIB. Internally, the PET has a 14K-byte BASIC interpreter and 32K bytes of random access memory (RAM) for storing program and data. There is an internal 24-hour clock that one can read with a single command. The PET can also be wired for sound; we used this feature to create an alarm. The GPIB is available through an edge connector on the rear panel.

Video switcher

To route video signals on schedule, we use a remote-controlled audio-follow-video switcher (a Fernseh 20 × 20, TVS/TAS 1000 with the optional RS-232 serial interface card). The inputs of this switcher are connected to all of our sources: the play output of 10 VTRs; the microwave relays from Davis, Berkeley, and Stanford; and our studio. The outputs are connected to the record in-

Fig. 2. The major components of our system are the PET microcomputer, the switcher, and the VTR control, connected with an IEEE-488 GPIB.

put of our 10 VTRs and to channels 7 through 13 of our on-site cable-TV system. Thus, we can record live classes for employees who have scheduling conflicts, and can play back these recorded classes and taped courses from our comprehensive library, as required.

To schedule the operation of the switcher, we interface the GPIB out of the PET to the switcher's RS-232 input with a TNW 232D serial converter.

VTR control

Because there are 10 VTRs, controlling them is more complicated than interfacing the switcher. Each of the 10 VTRs needs its own four-wire cable since we need to command each VTR to play, record, or rewind. Therefore, the VTR interface has to perform as follows:

- Receive the GPIB instruction.
- Decode that instruction into a discrete command for a single VTR.
- Fan out to that VTR.

Fig. 3. One of the 39 channels in the LLNL-designed interface. This was the only part that was not off-the-shelf.

- Buffer the VTR remote control line.

The ICS model 4882 instrument coupler satisfies the first two requirements: the coupler receives commands on the GPIB and converts them to 40 transistor-transistor-logic (TTL) outputs. The last two requirements had to be satisfied with a LLNL-designed interface. (Figure 3 shows one channel.) We built our interface to handle 13 VTRs. Three commands for 13 machines use 39 of the 40 lines available from the ICS coupler.

Interfaces

Both the TNW 232D interface to the switcher and the ICS 4882 interface to the VTR machines listen on the GPIB line from the PET. When addresses 20 through 24 are used, PET commands are converted to RS-232 serial words by the TNW converter. They are sent to the switcher. When address 9 is used, PET commands are converted to TTL logic outputs by the ICS converter. These logic outputs are buffered and fanned out to the various VTR machines.

Operation

We succeeded in helping the operator to connect a VTR to a load or source and to command that VTR to play or record at the proper time—and all this was done automatically with minimum de-

mands on the operator. This automatic action is called an "event," and its elements are:

- Day: the day of execution of the event.
- Time: the time of execution.
- From: the program source.
- To: where the program is to go.
- Command: what is scheduled to happen.
- Remark: identifying name of the program.

We wrote a program that keeps track of a 7-day week with a minimum time increment of one minute. Program sources can be the output of a VTR or a live class from an off-site campus. Program destinations can be a recording VTR or our closed-circuit TV cable network. Single-letter command options define what the operator wants to happen. A 13-space remark field contains the class name or ID number. When the operator enters this information, the program can tell what it is to do, when it is to do it, and what inputs and outputs are involved. The operator can see the event name so that the correct tape can be loaded beforehand.

When a VTR is connected to a selected switcher input, the VTR plays. When a VTR is connected to a selected switcher output, the VTR records. This is a normal switcher-oriented event, and the command for such an event is "N." In a normal event, the FROM/TO event information defines both the switcher command and the VTR command. Other operator commands allow the switcher or any VTR to be operated separately.

How the program works

How does the program bring together the operator's event information and the capacity for switcher and VTR control? The program can store more than 400 events. When these events are stored, the program gives them a reference number, which is appended to the event time. The time is then put in sequence in a time array for the day of execution.

The program constantly updates the time and compares the latest update with the event times stored for that day. When there is a match, a five-minute execute window opens that causes the switcher to switch and a VTR to be commanded according to the stored event information. Actual execution causes an execute flag to be set so that each event executes only once daily.

The operator, therefore, has only to enter the event information in the computer and put the tape in the VTR. The rest is automatic. Many of our courses have 20 or more lessons and are scheduled over a number of weeks. Normal events stay in the computer until deleted; therefore no further entries are required past the first week. In these cases, the operator simply takes the course number from the schedule on the screen and puts the appropriate tape in the proper player.

Convenient features for the operator

The operator has several command options available: review any sequence of events for any day, edit or delete any event, and independently command the switcher or any connected VTR from the keyboard. An all-inclusive mnemonic interpreter is built into the program so the operator does not work with the system channel numbers, but

only with the source and destination names, e.g., R1 is VTR 1, C8 is cable channel 8.

Epilogue

After the usual start-up problems in October 1980, the system has run since then without any problems and without requiring any changes. As a bonus, we have added a new capacity to run multiple off-hours events that allows the Laboratory to serve a growing number of swing-shift and graveyard-shift employees.

We have received about 25 requests for additional information from universities, colleges, public schools, commercial businesses, and the USAF Academy.

We plan to use the program to control other Laboratory systems that require timed operation (e.g., automatically recording broadcast programs that relate to Laboratory activities).