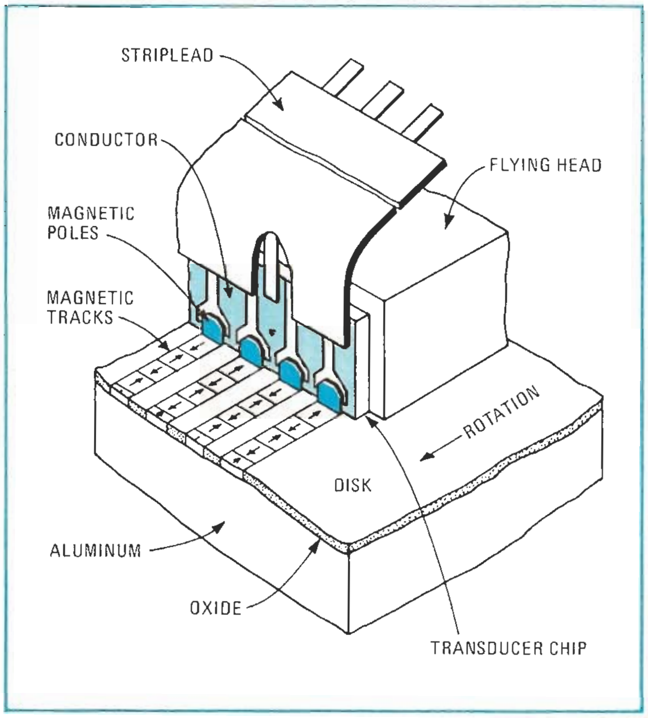
Small thin-film transducers point to fast, dense storage systems

In present high-speed disk-storage units, the number of bits per square inch is limited by the large size of the fixed read-write head—but really small magnetic heads can now be fabricated by integrated-circuit processes

by William Chynoweth,
Honeywell Information Systems Inc., Oklahoma City, Okla.,
and John Jordan and Wolfgang Kayser,
Honeywell Information Systems Inc., Phoenix, Ariz.



Flying head. Thin-film transducers (color), on their substrate chip, are mounted on the trailing edge of a head that "flies" less than 100 μin. above the surface of a rotating disk.

□ The fastest way to access the data in a magnetic-disk storage system is to span the disk tracks with a fixed head containing a separate transducer for each track. But the conventional fixed head also limits storage capacity because only 50 or so transducers can be squeezed across an inch of disk radius—the tracks read by a single fixed head can be only as close together as the transducers and their housing permit.

Moreover, the biggest total storage capacity and the fastest data transfer rates are obtained when bits are packed as densely as possible along each individual track. But densely packed bits require a short gap length in the transducer, although density is limited by other factors as well.

All this accounts for much of the present interest in replacing individual wirewound horseshoe-shaped transducers with much smaller, thin-film versions in which the magnetic structure and winding are fabricated in rows on the same substrate. The other important advantages of batch-fabricating the devices in this way are a high level of production repeatability and much reduced cost.

One thin-film-transducer project, called Pedro, was started in 1967 at the General Electric Co. and continued after 1970 by Honeywell Information Systems. But work on this technology is also under way at NCR Corp., Burroughs Corp., Minnesota Mining and Manufacturing Co., IBM Corp., and Sperry Univac in the U.S., as well as at Compagnie Internationale pour l'Informatique in France.

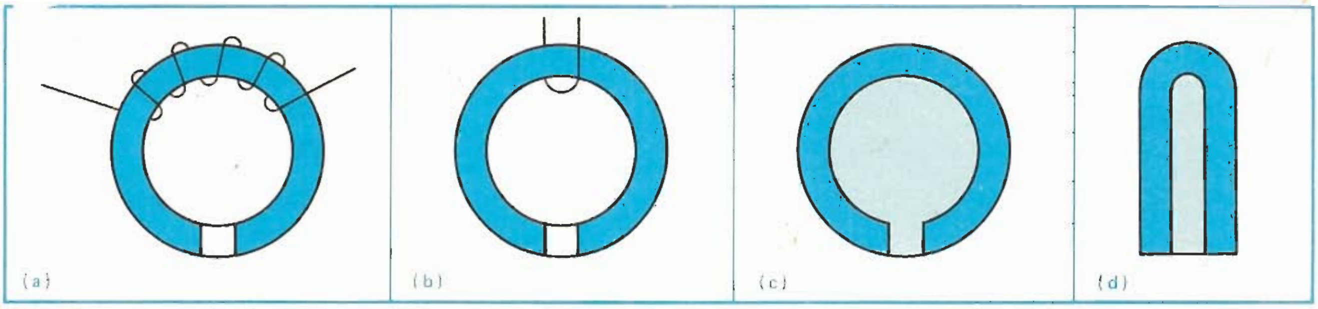
The aim of the GE-Honeywell project was to develop designs for thin-film transducers and to evaluate the technology's strengths and weaknesses. By 1970 enough progress had been made for several laboratory models of disk files to be built, using thin-film transducers to obtain track densities of 100 to 400 per inch of disk radius and flux reversal densities of 4,400 to 10,000/in. along the tracks. (Moving-head disk-storage systems attain similar bit and track densities because the single transducer in the head can be positioned very precisely, but their performance is much lower because moving the head into position is a relatively slow process.)

Honeywell's laboratory models were followed by an engineering model of a 6-megabyte disk file, built around standard disks like those used on commercial storage units. It has 100 tracks per inch and 5,100 flux reversals per inch, and it has demonstrated an uncorrected error rate of one in 10^9 bits.

By now, current trends in memory organization are under evaluation to see where the batch-fabricated thin-film heads can best be applied. That, presumably, will be in one or more products in the next generation of bulk-storage systems.

Thin-film transducers

The significant differences between conventional and thin-film heads lie in the construction of the magnetic recording transducer. Both kinds of transducers have the same elements—namely, a loop of magnetic material that is completely closed except for a small gap where the recording field is produced, and a winding of one or more turns of an electrical conductor. A varying current in this conductor creates fluctuations in magnetic flux



1. Evolution. Thin-film transducers have evolved from the classic, wound ring with a gap in it (far left), past ring shapes with either a single turn of ordinary wire or completely filled with a conductor (center left and right), to a conductor-filled horseshoe shape (far right).

that are captured by the recording medium moving past the gap. Conversely, externally imposed flux variations from the recording medium induce a fluctuating voltage in the conductor. But these elements take very different physical forms in conventional and thin-film transducers.

The thin-film transducer has evolved from the conventional ring-type with an air gap into a horseshoe shape in which the conductor fills the gap entirely. This "turn-in-gap" head is shown in Fig. 1 with just a single turn. But thin-film multiturn transducers have been investigated at Honeywell and elsewhere, in both vertical and horizontal form (Fig. 2).

The thin-film elements are fabricated by film deposition and photoetching processes that are closely related to integrated-circuit fabrication and can produce very short and shallow gaps and very narrow and closely spaced elements with great accuracy. A complete thin-film transducer may be only three times as thick and roughly the same height as the gap spacer in a conventional transducer, and multichannel magnetic recording heads can be fabricated as easily as single-channel heads.

The film's very thin cross section permits it to have an extremely short gap, which is essential in high-density recording—because closely spaced magnetic variations in the recording medium cannot be resolved by too long a gap. But this cross section also gives the transducer properties that are quite different from those of transducers made of bulk materials.

To begin with the advantages, track spreading and crosstalk between transducers are negligible. The very small broadside dimension makes the magnitude of side fringing fields drop off rapidly in real distance (as distinguished from distance as a proportion of transducer dimension), creating only small coupling of magnetic fields between neighboring transducers.

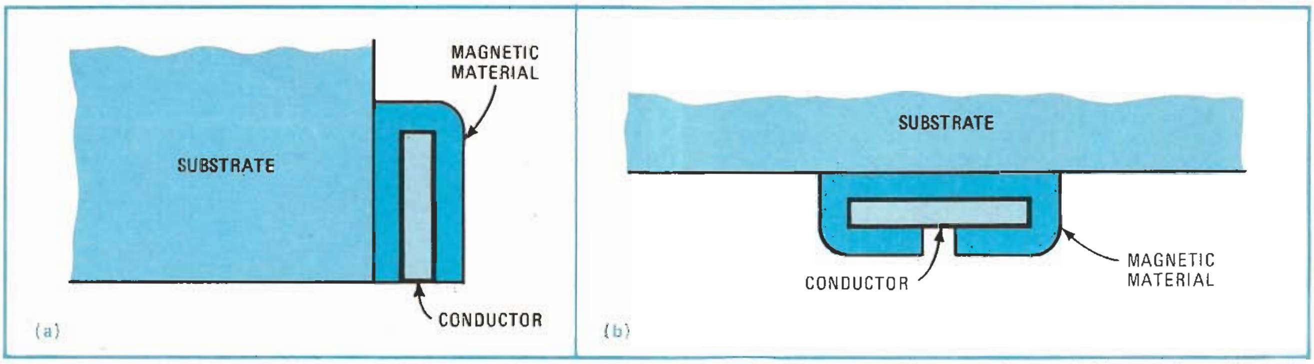
Also, resolution is improved because the thin pole tip is about as long as the gap. In conventional transducers, the tip is many times longer than the gap, but its corners are still within the magnetic field of the recording medium and can produce small but spurious signals that interfere with the gap signal. In thin-film transducers these "contour anomalies" produce effects in the same frequency range as those that are limited by the gap length and are more nearly in phase with them, so that their interference is less. As a consequence, the resolution for a given gap length can exceed that of a conventional transducer, particularly when the head is not in contact with the recording medium—as is usually the case in disk-storage units.

One disadvantage of vertical film transducers is poor low-frequency read performance. As in conventional transducers, the response to recorded variations with wavelengths greater than the length of the transducer drops off very steeply. These variations, which are also caused by the head contour, determine the low-frequency limit of the recording system. But in thin-film transducers, the rolloff begins at a much higher frequency than with conventional transducers.

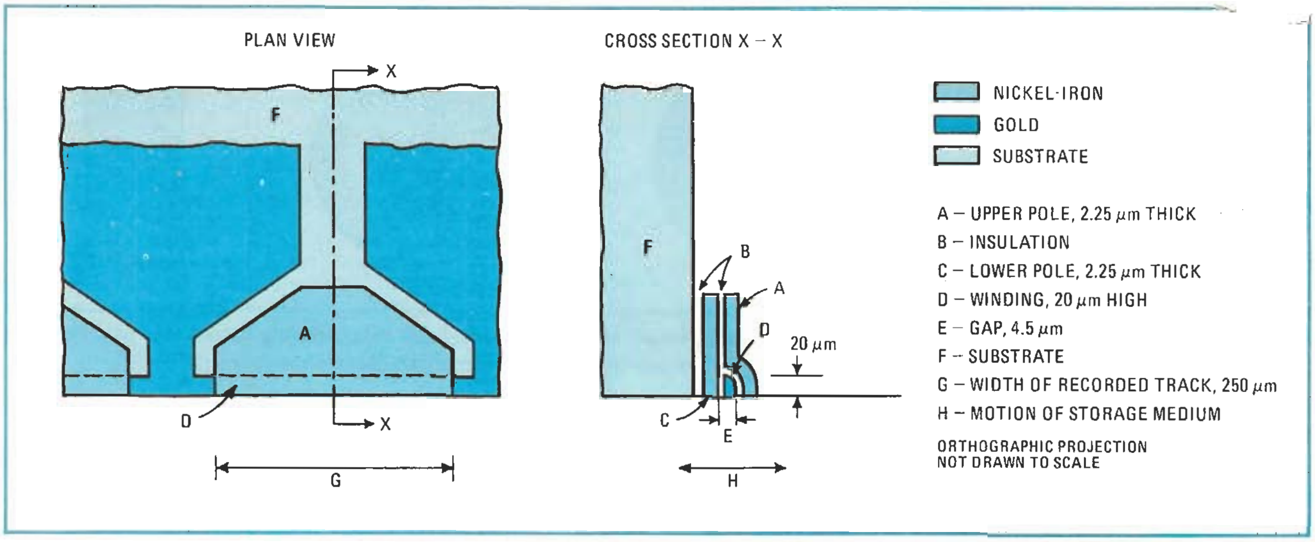
Furthermore, although the efficiency of a thin-film transducer is high, using the "winding" as the gap spacer results in an extremely high write-current density. And, although the read voltage is quite high, its absolute magnitude is very small.

Design considerations

The basic input parameters for the design of a thin-film multitrack head, like those for a conventional head, are linear recording density, track density, and oper-



2. Horizontal or vertical. Thin-film transducers can be deposited either vertically against one side of a substrate (left) or horizontally underneath it (right). Both orientations consist of successive depositions of magnetic and conductive materials, appropriately masked.



3. Orthographic projection. Vertical orientation of Pedro transducer comprises two layers of nickel-iron and a layer of gold. Gold layer extends upward to form pad for external connection. Note resemblance of cross section to the letter "h."

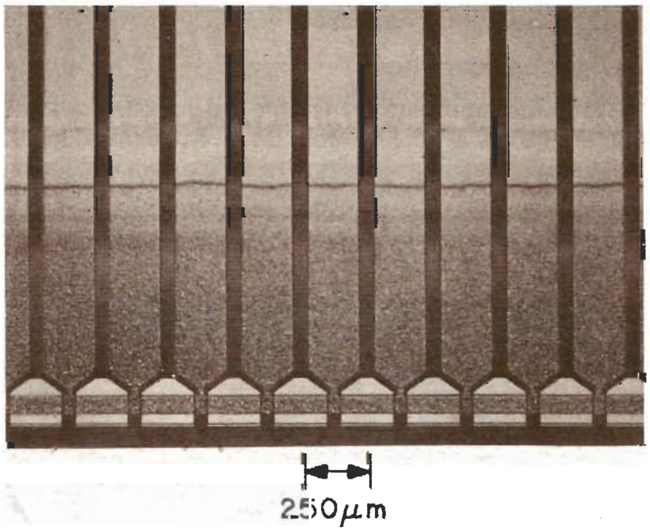
ating frequencies. Secondary parameters, derived from these basic inputs, are transducer dimensions, recording mode, and the height at which the transducer "flies" over the recording surface—usually 30 to 120 microinches, depending on the shape of the head and the kind of air bearing that the shape creates.

In the Pedro program the basic requirements were 100 tracks per inch and 4,400 flux reversals per inch, the same density as on the Honeywell DSU 180 or the IBM 2314 disk files. Standard commercial oxide coatings and conventional flying height of 70 to 100 µin. were used. The gap length was chosen as 4.5 micrometers, which is about 180 µin.

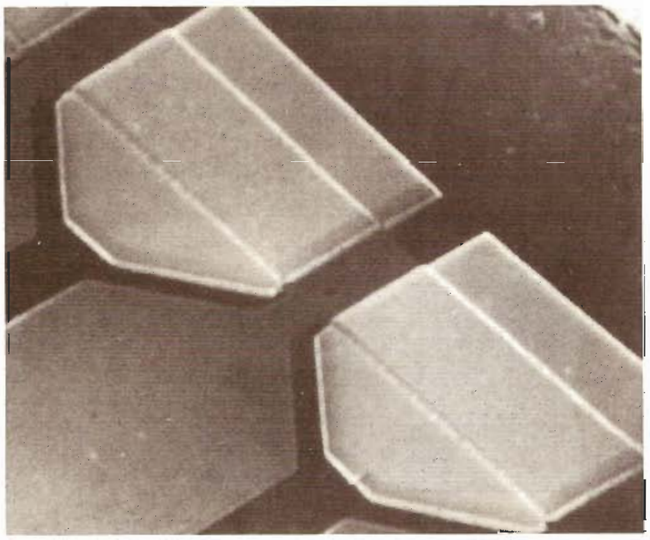
The Pedro transducer is a two-pole vertical type made of materials chosen for compatible thermal expansion coefficients and etching characteristics, as well as the obvious magnetic or electrical properties. An insulated design was chosen in which the metallic layers are separated by insulating layers.

Since the larger the number of transducers on a head, the lower the cost per track, it's important to reduce the number and complexity of transducer connections. As shown in Figs. 3, 4, 5, and 6, two adjacent transducers share a connecting pad. An alternative configuration would be to connect one side of each transducer to a common bus bar. With either configuration the number of leads from a head is one more than the number of transducers, permitting a flexible, flat multiconductor strip-lead to be used for a simple connection to the transducers. But the shared-terminal construction has better thermal performance because it maximizes the conductor area and cross section between transducers, while also maximizing track width for a given track density.

Ideally, the write field produced by a transducer would affect a magnetic storage medium of indefinite thickness only directly under the transducer gap. But ideal conditions are never realized; one departure is in the use of the flying head, which is necessary to reduce wear and tear on the recording surface. This separation



4. Worm's-eye view. Microphotograph shows 10 transducers on a common substrate, before excess at bottom has been ground away. Gray bands, connected to vertical pads, are the transducers.



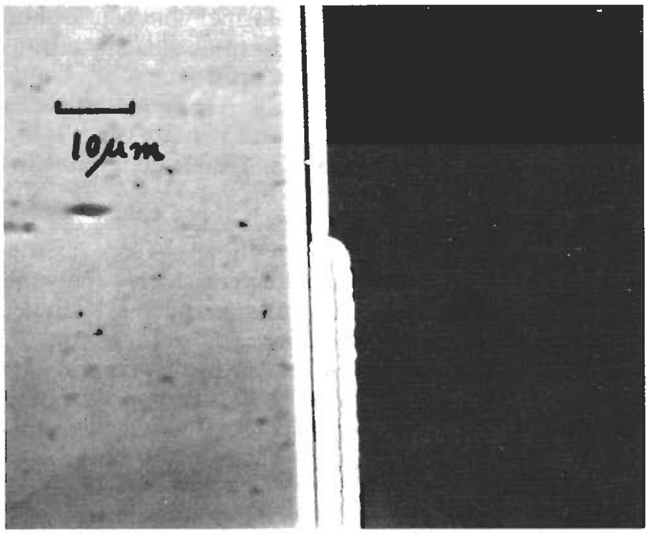
5. Detail. This photo, made with a scanning electron microscope, clearly shows how the nickel-iron deposition overlies the conductive gold layer, which extends leftward toward top of transducer.

of the recording surface from the transducer gap combines with the fringes of the write field (always found outside the gap) and the finite thickness of the magnetic medium to affect the medium at a distance from the gap. As a result, an isolated magnetic pulse spreads out, and closely packed pulses are reduced in amplitude—a phenomenon called pulse crowding.

Recent analyses of thin-film transducers have shown that the write field is less than that of a conventional transducer at distances greater than one gap length from the center of the gap, in a direction parallel to the recording surface, and may even become opposite in sign. This difference significantly improves resolution and reduces the problems of pulse crowding found with conventional transducers.

Likewise, the reading performance of a vertical thin-film transducer differs from that of a conventional transducer because of the thinness of the poles and the "turn-in-gap" configuration. In any transducer the voltage across the output terminals is generated by the sum of two changing flux patterns: a high-resolution part carried by the poles and linking the entire winding, and a low-resolution part carried through the air and linking at most only part of the winding. In conventional transducers, the winding has many turns and is remote from the gap, so that the airborne part generates a voltage that is only a negligible fraction of the total. But in thin-film transducers, with a one-turn "winding," the airborne flux is a much larger proportion of the total, and creates a more variable output.

Furthermore, the small uniform cross section of the film transducer and the limited permeability of materials such as nickel-iron and iron-cobalt, of which the transducer poles are made, results in leakage between the poles. Therefore not all of the flux entering the pole tips from the recording passes around the conductor. The ratio of the flux passing around the conductor to the total flux entering the pole tips can be calculated. It is greater than 0.95 for a permeability in excess of 500 and a 20-μm conductor height (Fig. 3). Because the mathematical expression for the ratio involves the square root of the permeability but the direct height of the conductor, the effect of the height is greater than that of the permeability. The ratio drops off quickly for a permeability below 200; it also decreases more or less linearly for taller conductors.



6. Actual scale. In another view, this microphotograph shows the nickel-iron layer "dropping off" the top of the gold layer. It also indicates true scale of the cross section shown in Fig. 3.

Because the transducers are very small while the write currents are relatively large, the current density in the conductor can reach 3×10^6 amperes/cm^2, dissipating as much as 0.25 watts and corresponding to a power density of over 20 megawatts/cm^3. These are orders of magnitude higher than in conventional transducers. To keep the temperature low enough for reliable operation, heat must flow readily along the path from the current-carrying conductor through the intervening layers of metal and insulation to the substrate.

Thermal characteristics

A theoretical thermal analysis under write conditions shows that the transducer's thermal and electrical conductances deteriorate rapidly above approximately 2.45 A (Fig. 7). However, the normal operating range is well below this nonlinear region. Theoretical analysis also predicts a temperature rise of 29°C in the conductor for a current of 1.5 A.

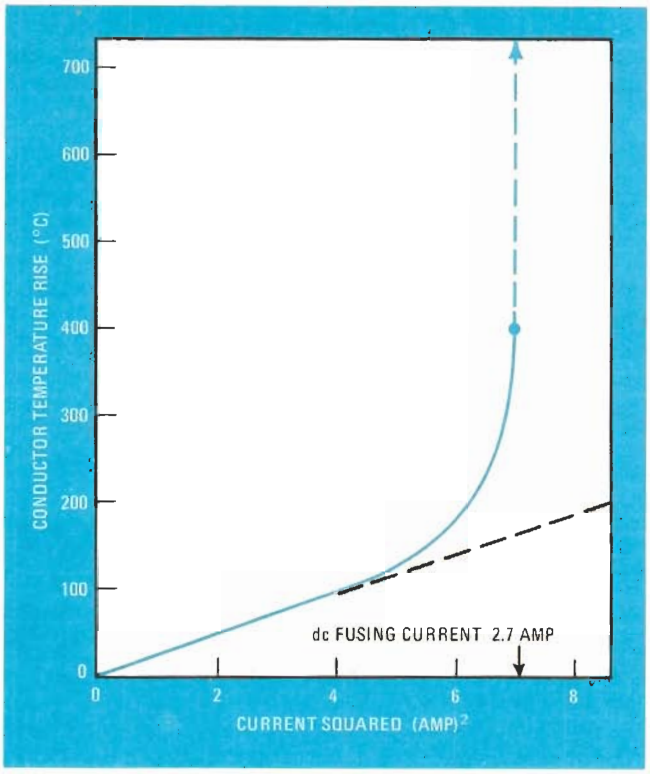
This has been experimentally verified, using the gold conductor in the transducer as a resistance thermometer. With the shared-terminal design a four-point-probe resistance measurement is possible. As shown in Fig. 8, if a current is passed through any one transducer, the actual voltage across that transducer can be measured with a high-impedance voltmeter connected to any pair of leads that have both current leads between them. Thus if the current through the conductor, which is made of gold, is accurately known, the conductor resistance can be calculated, and converted to temperature using the known relationship of resistivity to temperature for a thin film of gold.

Such measurements as these indicate that a temperature rise of 25°C, which is 4° below the predicted rise, is typical for these dimensions at a peak operating current of 1.5 A. Other measurements with pulsed currents up to 2.0 A showed that the thermal rise time is less than 60 microseconds. The turn-on time constant increases dramatically as the thermal nonlinearities come into play—but again, these are found well above the operating range. Such time constants are much shorter than ordinary data block periods in a disk file, and the demonstrated temperature rises are small. Thus reliability degradation caused by thermal cycling will not be a problem in storage systems using thin-film heads at the flying height in this model.

Head fabrication

The transducer is a five-layer, photoetched, thin-film structure, batch-fabricated on a thermally oxidized 1-0-0 silicon substrate. The silicon wafer is inexpensive, flat, smooth, and a good thermal conductor. Long rows of transducers extend right across the wafer, which can be readily scribed and broken into chips of any desired size. The long rows provide maximum flexibility in this regard, while the 1-0-0 crystal orientation simplifies the scribe-and-break step.

Standard sputtering and photo-fabrication tech-



7. Thermal response. Theoretical analysis, confirmed by experiment, shows reduced conductance and sharp temperature rise at high current, ending in destruction where curve becomes vertical. Normal operation is well down in linear part of curve.

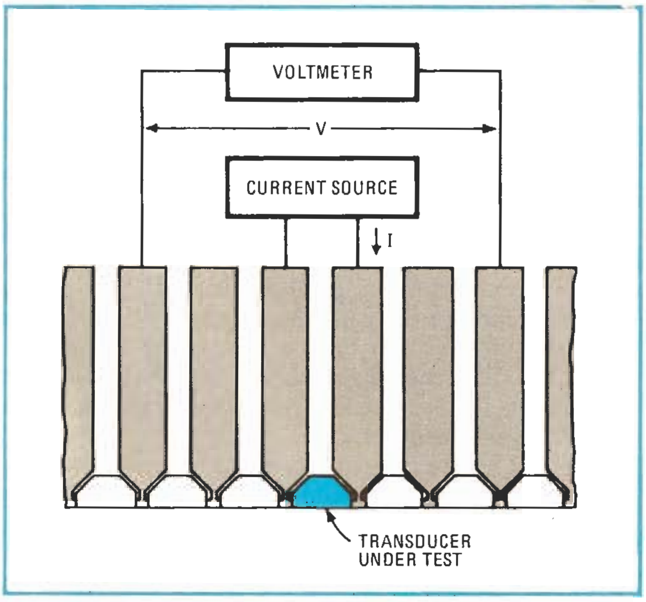
niques are used in depositing the five thin-film layers. These are, in order, the bottom magnetic pole material, the bottom insulation layer, the conductor layer (actually a three-part layer—.015 μm of chrome for adhesion, 13 μm of sputtered gold, followed by an electroplated layer of gold of the required thickness), the top insulation layer, and finally the top magnetic pole. All but the bottom insulation layer are also either etched or masked to align their respective patterns.

The thin-film transducer seems well adapted to a multi-track head for a disk file. The most convenient assembly locates the chip on the rear end of a standard slider, riding on the air cushion between it and the recording surface. A protective cover glass should be cemented over the row of transducers. This configuration is used in the present engineering model.

To connect the transducer chip to the circuit board, a flexible multilead cable is required. A suitable cable can be made by photoetching a multiconductor pattern on copper-clad Kapton, which is flexible, yet can stand the reflow soldering temperature without distortion. The strip-lead fans out from the 0.010-in. spacing of the chip connection pads to the 0.025- or 0.05-in. spacing at the circuit board.

Transducer/electronics interface

As described previously, at a nominal flying height of about 80 μin, the transducer requires drive currents of 1.0 A or more to produce the required magnetic fields for recording on standard disks. But the single-turn transducer has a resistance of about 0.2 ohm, and the combined impedance of transducer and associated strip-leads is about 1 ohm at 2.5 megahertz. Meanwhile, the single-turn transducer produces a peak-to-peak read signal of about 120 microvolts at a recording density of 4,400 flux reversals per inch.



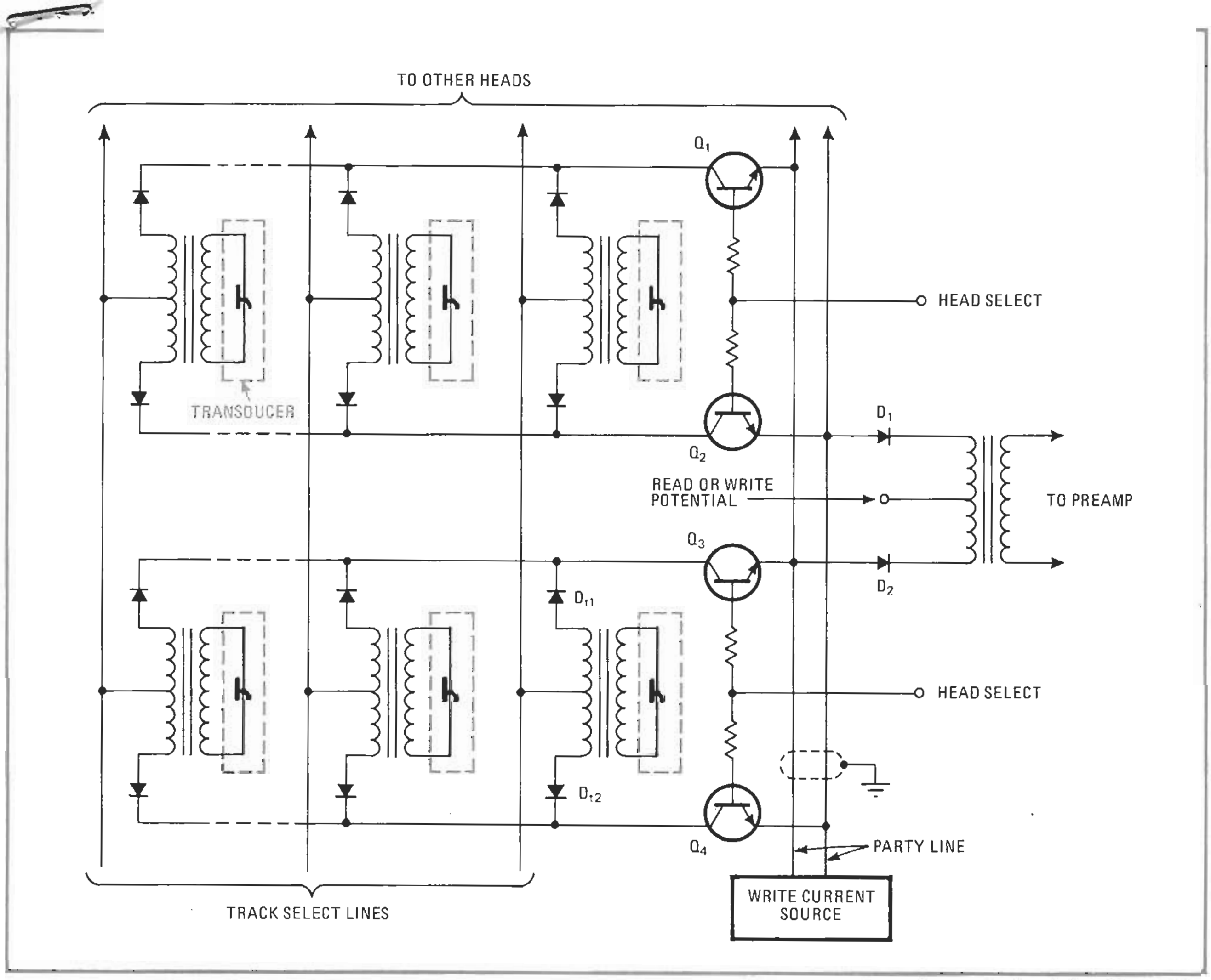
8. Resistance measurement. When current is passed through any one transducer in an array, voltage drop can be measured from any two other leads that have both current leads between them. Resistance and temperature are calculated from the voltage and current.

To drive and sense the single-turn transducer directly with integrated circuits is difficult with such a high drive current and low signal level. Thus discrete-component circuits have been used in the present model. The circuits use a single transformer for both read and write, to reduce the drive circuit's current requirements for writing and to increase the signal level for reading. Each transducer has a separate transformer, and the secondary winding of the transformer is center-tapped. The transformer has a turns ratio of 1:8 for write and 1:16 for read, through this center tap, thus reducing the required drive current by a factor of nearly 8 and increasing the sense signal to more than 1 millivolt.

To keep the transducer-transformer connection short, the transformer must be close to the head. Since transformers for all the transducers must fit in this limited space, they must be very small. To meet these constraints, the transformers are wound on pot cores, which are small cup-shaped pieces of magnetic material with a single post in the center of the cup.

In pot cores the windings go on the posts; the flux path closes through a cover or another pot core inverted over the first one. This arrangement shields the windings from external electrical interference and physical damage, while closing the magnetic path around the windings in three dimensions. But in the experimental disk file using the thin-film heads, the cores are used singly, stacked one on top of another so that the magnetic path of each one closes through the back of the next.

The presence of a transformer imposes some constraints upon the recording code. Normally the magnetic transducer is directly coupled to the write driver, thus responding to direct current. But the transformer



9. Transducer selection matrix. Combination of track-select and head-select lines picks one transducer, hence one track, for either read or write. Transformers (pot cores) increase write current and step up read signal. The h-shaped symbol represents the transducer (Fig. 3).

used with the thin-film transducer has a low-frequency cutoff of about 50 kilohertz. These characteristics would be unsatisfactory with the non-return-to-zero-inverted code, in which writing a continuous string of 0s requires the passage of a direct current. Likewise, any code that allows an unbalanced write-current sequence to be repeated indefinitely has a net dc requirement, which again won't pass the transformer.

But with certain codes—for example, the double-frequency and phase-modulation codes, or codes that permit only certain allowed sequences—a repetitive unbalanced write current sequence cannot occur. These codes therefore have no long-term dc bias and hence are suitable for use with a transformer.

The presence of a transformer causes no such problems in the read mode because sensing through rate of change of flux eliminates the need to detect direct current. However, the transformer's low-frequency cutoff may cause an undesired phase shift.

Transducer selection

Since every track has its own read/write transducer, selecting the transducer selects the track. The selection circuits must not significantly degrade the write current or the read signals. They must also be low in cost, so that they do not negate the cost advantages of batch-fabricated thin-film transducers. Low cost is achievable if each flying head carries at least 20 transducers, which can be done easily with the Pedro structure. The engineering model, which uses standard disks with 374 tracks, has 12 flying heads with 32 transducers on each head.

The selection circuits form a matrix (Fig. 9) in which the track select lines are the columns and head select lines form the rows. The selection transistors are drivers when writing and saturated switches when reading. One track-select line addresses, say, the innermost track served by each of several flying heads, while selection of one of those heads isolates the selection to one transducer and the track it serves. A double "party line" interconnects all selection transistor pairs with the write current source and with the read preamplifier. ☐

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