INTRODUCTION

H. D. Toombs and T. E. Hasty have described a technique utilizing ferromagnetic resonance to obtain nondestructive readout in thin permalloy film memories. A study has been made by the authors to determine how this technique could best be utilized in medium and large sized computer memories. The study culminated in the construction of a 32-word, 24-bit film plane tester utilizing absorption resonance readout which served to provide data on the resonant behavior of various films and to lend practical experience in the design of a resonance memory.

Resonance absorption may be demonstrated by subjecting a ferromagnetic material sample to a steady magnetic field which (viewed classically) sets up an axis of precession for the electron spins responsible for the material's magnetic moment. If a R.F. field is now applied perpendicular to this axis with a frequency near the natural precession frequency given by the Larmor relation \( \omega = \frac{ge}{2mc} (4\pi M H_K) \) (gaussian units), the spins will begin to precess in sympathy, absorbing energy from the R.F. source. In the present application the steady field is provided by the internal anisotropy field \( H_K \) of the material. Due to the shape anisotropy of a thin film, the precession is distorted so that the magnetization vector \( M \) remains very nearly in the plane of the film. This fact modifies the Larmor expression so that the resonant frequency is given by \( \omega_0 = \frac{ge}{2mc} (4\pi M H_K) \) where the subscript on \( \omega \) implies that no external field other than the rf field is applied. If an external field \( H_{ap} \) is superimposed parallel to the external anisotropy field this expression becomes

\[
\omega = \frac{ge}{2mc} (4\pi M |\vec{H}_K + \vec{H}_{ap}|)^{1/2}
\]

Thus the resonant frequency shifts above or below \( \omega_0 \) depending upon whether the magnetization vector \( M \) is parallel or antiparallel to \( H_{ap} \). It is this phenomena that is used to nondestructively determine the magnetic state of film cell.

Figure 1 shows schematically the configuration of a resonance memory. Power from a uhf oscillator is equally distributed by means of a power splitter over the digit lines. Film cells lie under the digit lines such that their anisotropy axis is perpendicular to the uhf field direction. A small fraction of the power is therefore absorbed by each cell, the remainder proceeding to the end of the line to bias a demodulator detector. The operating frequency is set somewhat below the resonant frequency of the film cells as shown in Fig. 2. Interrogation of the memory is
Figure 1. Configuration of resonance absorption memory.

Figure 2. Resonant absorption-frequency characteristics. accomplished by pulsing a word line thereby reducing or augmenting the absorption depending on the cell's magnetization. This change in absorption is demodulated at the detector so that an output pulse is produced which is a replica of the interrogate pulse with a polarity dependent on film state.

Writing is done by the technique conventional for film memories. Note however that the film axis direction dictates that the role of the word and digit lines be exchanged for the writing operation. This necessitates transposing the data to be stored. Other writing schemes involving separate write conductors to circumvent this difficulty were considered but these were not developed in this study.

DESIGN CONSIDERATIONS

Selection of an Operating Frequency

From the design viewpoint a low absorption frequency is preferred because this favors oscillator efficiency, detector efficiency, and ease of matching. It was found by experiment that obtaining good control of resonant absorption with an external field requires the use of film with an $H_K$ of 5 oersteds or greater, and a frequency of 550 megacycles or greater. The frequency of 550 mc was satisfactory for the design of a solid state oscillator using a 2N3375 transistor having an efficiency above 40 percent, and also for the design of a transistor detector. A higher frequency and $H_K$ can be used but no advantage was recognized. Operation below film resonance was much preferred to operation above resonance both because of greater signal output and because circuit design problems significantly increased at the higher frequencies near 1,000 megacycles.

Thin film absorption characteristics in terms of signal output versus frequency are shown in Fig. 3. Figures 3a, 3b, and 3c show the need for selection of film having relatively low dispersion (under $2^\circ$) and a moderately high $H_K$ of 5 oersteds or greater. The R.F. line was 5.5 mil wide and of 50 ohms impedance.

Figure 3a shows the effect of $H_K = 3.5$ oersteds and dispersion of ($\alpha_90$) of 10$. The signal output versus frequency for a stored 1 is shown. Too much creep occurred on this film to show a stored 0 when the applied read field was opposite to the magnetized state of the cell.

Figure 3b shows some improvement for $H_K = 3.8$ oersteds and dispersion of $4^\circ$. A signal was obtained for a stored 1 and stored 0.

Figure 3c shows the 1 and 0 output versus frequency for films having $H_K = 5.3$. In this film $\alpha_90$ was less than $2^\circ$. The externally applied field was generated by passing 300 milliamps through a 60-mil-wide conductor adjacent to the cell in all cases.
A THIN MAGNETIC FILM COMPUTER MEMORY

THIN FILM CHARACTERISTICS

\[ H_k = 3.8 \text{ OERSTEDS} \]
\[ H_c = 2.5 \text{ OERSTEDS} \]
\[ \alpha_{90} = 1^\circ \]

\[ \text{Figure 3b. Resonant absorption readout of 1000Å-thick permalloy, 30 x 60 mil size. Applied field to generate signal is in direction of stored 1.} \]

\[ \text{Figure 3c. Resonant absorption readout of 1000Å-thick permalloy, 30 x 60 mil size. Applied field to generate signal is in direction of stored 1.} \]

The reason for the inflections in signal amplitude with increasing frequency for films with low \( H_k \) and high \( \alpha_{90} \) is not understood by the authors. The line and detector for these measurements had an SWR of less than 1.1 over the frequency range shown. A diode detector was used for these measurements.

CALCULATING THE SIGNAL MAGNITUDE

Neglecting copper and dielectric losses the power attenuation down a digit line is given by \[ \frac{dP}{dn} = -kP \] or \[ P = P_0 e^{-kn} \] where \( P_0 \) is the input power, \( n \) is the cell number, and \( k \) is the fraction of the power reaching a cell that is absorbed by that cell. If one of the cells is interrogated, its power absorption is changed by \( akP \) where \( a \) is the fraction of the absorption that can be controlled by the word pulse. Considering the attenuation due to the remaining cells as given above, the power signal at the output is \[ \Delta P = akP_0 e^{-kN} \]. This signal is maximized with respect to \( k \) when \( kN = 1 \). Thus to obtain the best power signal the cell size must be adjusted to produce an attenuation down the line (less copper and dielectric losses) of \( 1/e \) or 4.3 dB.

Under this condition the signal power at the last cell where the R.F. lines connect to the detector is \[ \pm \frac{P_0}{e} \left( \frac{a}{N} \right) \] where \( N \) is the total number of cells along the digit line.

The fraction \( a \) was measured for a number of cells on a 50-ohm strip line. A power meter monitored the output and input. A large cube coil placed over the line applied a field of 0, +1.4 or -1.4 oersteds. This was the largest field that together with the R.F. would not permanently change the stored magnetization of the memory cells. R.F. level was 10 milliwatts. With the data adjusted for \( 1/e \) total attenuation, the power ratios measured were:

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Line Loss</th>
<th>Variation in Line Loss with Applied Field</th>
</tr>
</thead>
<tbody>
<tr>
<td>450 mc</td>
<td>4.3 db</td>
<td>-0.81 db</td>
</tr>
<tr>
<td>550</td>
<td>4.3</td>
<td>+0.38</td>
</tr>
<tr>
<td>640</td>
<td>4.3</td>
<td>-1.17</td>
</tr>
<tr>
<td>640</td>
<td>4.3</td>
<td>+0.58</td>
</tr>
<tr>
<td>640</td>
<td>4.3</td>
<td>-1.53</td>
</tr>
<tr>
<td>640</td>
<td>4.3</td>
<td>+0.76</td>
</tr>
</tbody>
</table>

It was found that 10 milliwatts peak power at 550 megacycles was near a practical maximum for the 5.5-mil-wide 50-ohm R.F. line used. Above this value the stored information might be lost due to creep on readout. This power provided a peak calculated R.F. field of close to 1 oersted. The limit
on power is influenced by the R.F. line dimensions and the properties of the thin film. The power at the output with 10-milliwatt input would be

\[
\frac{0.010}{e} \text{ watts ± the signal power}
\]

If all the memory cells at 550 mc could provide a -1.17 db change, then each cell would provide -1.17/n db change of the output power.

For 32 cells used in the memory film substrate transistor was used in place of a diode for detection tester described later, a -1.17/32 or 0.0365 db change could be expected, assuming the cells were adjusted so that 32 cells provided 4.3 db attenuation. In practice 30 x 60 mil cells 1,000 A thick with \( H_K = 5.3 \) will closely achieve this. The R.F. level change in a 50-ohm line using 10 milliwatts into the input would be 0.43 volts +1.55 millivolts. This modulation was confirmed using a General Radio detector on the above-mentioned film tester.

Figure 4 is a circuit diagram of the detector and signal amplifier used on the film tester. A 2N918 since it was possible to obtain a signal voltage gain of 32 as compared to a diode. This gain avoided noise problems in the following amplifier and resulted in a better signal-to-noise ratio being obtained as compared to a diode.

Detector noise as observed on an oscilloscope was below 0.1 volt peak at the amplifier output. Referred to the input at the emitter there is a voltage gain of 8,000, thus noise peaks at 12.5 microvolts for this particular detector. Turning the oscillator on and off makes almost no difference to the observed noise so that the solid state oscillator
driving 10 milliwatts into the R.F. lines does not appear to be a principal source of noise. It is believed that a better noise figure could be obtained with an improved detector design.

The observed signal-to-noise ratio was 120 to 1 for a stored 1 and 70 to 1 for a stored 0. If the number of cells on the R.F. line were increased (by 8) to 256, the signal noise would be 15 to 1 and 8.7 to 1. This assumes that attenuation and signal from each memory cell was reduced by 8 to 1 to maintain optimum line attenuation. Adjustment of cell width, thickness, and $H_K$ could achieve this. Since a considerable allowance must be made for variations in detectors, standing waves, and variations in memory cell performance, this represents a practical limit for the setup as tested. However, a better detector might be designed and better film might be made so that extension of the number of memory cells per R.F. line is quite possible.

**R.F. LINE IMPEDANCE**

The initial choice of a 50-ohm R.F. line was dictated by the convenience of using existing fittings, cables, and R.F. measuring equipment. However, given a required memory cell center to center spacing (80 mils was initially selected), the lower the line impedance the wider the strip line must be, assuming spacing to ground is fixed by glass substrate thickness. Thus R.F. line-to-line coupling will be increased as the spacing between lines is reduced. There is therefore a lower limit of impedance which is reached for a given layout when R.F. line-to-line coupling becomes excessive. The worst-case coupling that must be considered is all of the lines to one other line. If all the bits being read out are 0's (or 1's) except one bit, then R.F. coupling will provide a competing signal of polarity which will reduce the required signal.

It was determined experimentally that the absorption (and therefore signal output) from a given memory cell increases almost linearly until the cell is three times the width of the R.F. line. This is probably true only for the narrow (5.5 mil) R.F. lines used where fringing fields are excessive. Spacing to ground was 6 mils. It was also found that writing into a memory cell by rotation of its magnetization required approximately the same word current whether the word line was 1/6 of the cell width or equal to the cell width. This was due in
part to fringing fields, in part to the fact that demagnetizing fields prevent alignment of the edge of a thin film cell in the hard direction and in part to substantial magnetic coupling from region to region within the thin film cell.

The disadvantage of a narrow line to obtain 50 ohms did not appear very substantial. The advantage of wider R.F. lines might be the use of greater R.F. power without causing magnetic creep during reading. The line current \( I = \frac{P}{Z} \). Approximately,

\[
Z = \frac{\text{spacing to ground}}{\text{conductor width}} \times \text{constant } K_1
\]

but space to ground is determined by glass substrate thickness so

\[
Z = \frac{K_1}{\text{Width}} \quad \text{and} \quad P = \frac{\text{Power} \times \text{Width}}{K_1} = \frac{P_i W_i}{K_1}
\]

The R.F. magnetic field on the surface of the flat strip line is approximately given by \( H_{RF} = \frac{I \times K_2}{\text{Width}} \)

\[
= \left( \frac{P}{W_i} \right)^{1/4} K_s
\]

so that if peak R.F. magnetic field is the main cause of creep during reading it can be reduced as the inverse root of the R.F. line width, although in most practical layouts R.F. coupling will make lines of less than 50 ohms impractical apart from the problem of making special fittings cables and measuring equipment.

The principal source of coupling between the R.F. lines was capacity coupling between the R.F. lines and the digit write lines (see Fig. 5). The layout in Fig. 5 has 768 small capacity coupling points at the matrix crossover points. When 23 R.F. lines are driven with equal R.F., the worst-case coupling on the 24th line was measured as 16 db down on the driven lines. The 24th line is matched at its input with 50 ohms for this measurement. Removing the digit write lines reduced the R.F. coupling for this test to 35 db below the driven lines. It would not therefore be practical to extend this layout much beyond 32 memory cells per R.F. line. However if a 1-mil metal sheet is placed over the R.F. lines, and it is suitably grounded at intervals, then almost no R.F. will be found outside the thin metal top plate. If the digit write lines are insulated and placed over this sheet they no longer form a coupling network. However at a readout rate of the order of 1 megacycle the field from these lines will penetrate the thin metal shield and permit readout of words from the memory, and also permit information to be written in the memory.

**THE MATRIX TESTER**

A memory thin film tester was designed and constructed both for testing film for use in an R.F. absorption type memory and to determine the magnitude of the problems in reaching a practical design for a useful memory. Figure 6 shows the completed tester. Thin film substrates could be inserted under a grid of R.F. lines (24) and digit lines (32) as shown in Fig. 5. To obtain information on writing in the memory, and reading the memory, it was arranged that the 768 switches shown would provide unlimited variation of the pattern to be written, and a check of the contents on a subsequent read cycle. A complete read write cycle is repeated at a 30 cycle rate so that a flicker-free display could be obtained (on the CRT shown) of the memory contents or error pattern or switch pattern. Word current, digit 1 and digit 0 current, and read current were continuously variable by adjusting the power supplies shown so that the effect of any variable could be seen on an error pattern. To determine creep and stability, the tester can be switched to read only and the error pattern observed. The low clock frequency of 25 kilocycles made possible a relatively simple layout using pulse rise times of about 0.5 microseconds and allowed recovery time for drive transformers when writing. Even so some shielding of the 1.5-amp maximum word currents was necessary.

Both 1 and 0 signal outputs when reading were checked for signal level by voltage comparators whose trigger point was continuously variable from 2 to 7 volts. This enabled a memory cell to be identified rapidly if its readout signal was below the set margin. Display lights and stop on error provided the address of a memory cell that had a weak output. Identification of a memory cell on the CRT display was quite easy and this feature was normally used. The setup as shown allowed easy connection of a signal generator to any R.F. line so that a faulty memory cell could be tested over a range of R.F. frequencies to determine whether its resonance characteristics caused a read error. It was as a result of such tests that 550 megacycles was selected to make most of the film planes operate correctly.

Word currents were variable from zero to 1.5
A THIN MAGNETIC FILM COMPUTER MEMORY

amp through a 5.5-mil wide R.F. strip line. Digit currents were variable 0-300 milliamps through a 60-mil wide strip line.

Figure 5 shows the R.F. lines which are placed next to the thin film. The substrates are loaded under the matrix with the magnetic film on the top side of 6-mil glass. Four grounding screws must be removed to change the glass substrate.

The digit lines were divided into 3 12-mil lines spaced 12 mils apart to reduce capacity loading on the R.F. lines. This precaution was just sufficient to make the 32-word layout usable from the R.F. coupling viewpoint. As mentioned earlier, the R.F. coupling problem can be reduced by an order of magnitude if a "Tri-plate" layout is used with a thin ground plane separating the digit lines from the R.F. lines. It appeared that this could be a solution to the R.F. coupling problem in larger memories.

The R.F. source was a series-tuned oscillator using a 2N3375 transistor. This oscillator drove a strip line power splitter etched on a 10-mil glass epoxy copper laminate. A transformation from 50 to 2 ohms was made with a tapered line and 25 lines connected to the 2-ohm point through 50-ohm resistors to 25 coax lines. The resistors were required to absorb the reflected waves which had a strong effect on the signal amplitude.

The use of 50-ohm cables and connectors was almost essential in the R.F. system to allow measurements of power loss, SWR, and coupling. These problems must be well understood before making a memory layout comprising etched card strip line configurations which would not necessarily provide accessibility for making measurements.

In testing thin film planes a rather severe "creep" test is made when writing information because of a peak R.F. field below resonance of near 1 oersted acting in the hard direction for the film. Both R.F. and d-c were passed down the R.F. lines when writing. However, it did not prove necessary to turn off the R.F. when writing since the same digit current was used for reading and writing, and creep would occur on the read cycle if it affected writing. Nickel iron cobalt films were used with an overlay of copper diffused into the film. This appreciably helped the creep problem. A number of copper diffused substrates were tested and found to have reasonable write current margins. In addition they did not lose information on continuous read.

The use of a 5.5-mil word line for writing into a 30-mil wide memory cell did not appear to affect the digit current margins appreciably as compared with the use of a wider word line. However in testing 20-mil wide word lines (which required a strip line transformer for impedance matching at both ends) there was so much R.F. coupling because of the increased capacity coupling to the digit write lines that this test was not continued.

The R.F. absorption memory has a peculiarity that the word lines (R.F. lines) when writing become the digit lines when reading. Thus the memory must be loaded with one digit of every word at a time requiring that the information be prepared in this form before loading a memory. If it were required that one digit of each word be read out at a time (perhaps in searching for information) then
rotating the information format through 90° would be an advantage.

DESCRIPTION OF A HYPOTHETICAL 4K WORD MEMORY

Figure 7 shows how an NDRO memory using resonant absorption phenomena for reading might be laid out to take advantage of the fact that R.F. is only required in the small block of the memory being interrogated. The block diagram shows a layout using 16 blocks with 16 separate oscillators and the present predicted limit of 256 memory cells per R.F. line. There is a transient settling time of 3-4 microseconds for the detector shown on Fig. 4 (except that C₂ was reduced to 200 picofarads) after switching the oscillators. No detectable noise or output was observed at the detectors (that resulted from the read current) when an R.F. oscillator was turned off because the detectors include a ¼-wave 550-megacycle grounded stub which would provide a short circuit for transients of lower frequency. It should therefore be possible to parallel the detectors to a common sense amplifier as far as read noise is concerned. Switching the detectors on and off simultaneously with the oscillators is not costly in terms of components if this should prove necessary.

SUMMARY

Possible Advantages of Resonant Absorption Readout

1. The use of R.F. oscillators provides an extra switching dimension which might provide economies over word selection usually used to read out thin film memories. This is more likely to be relevant if the memory is very large than for the size of memory considered.

2. In large memories it might be economical to use relatively long pulse rise times to read out thin film. The resonant absorption readout technique makes this possible without reducing signal amplitude since the output signal is not proportional to the rate of change of the read current, but only dependent on the R.F. frequency and absorption characteristics.

3. In large memories the operating power could be quite low compared to other thin film types because very little power is required by a block of memory not being used.

4. Current margins for readout can be quite wide. Temperature compensation should not be required.

5. In some applications, turning the information format thru 90° could be an advantage, particularly when it is required to address bits within words rather than complete words.

Disadvantages

1. The present limit of 256 cells per R.F. line and detector may not prove sufficiently attractive economically. However it may be possible to make considerable improvements with better magnetic film and a better detector.

2. Turning the information format through 90° is likely to be a disadvantage for many applications. The use of an extra set of write conductors to correct this (in zigzag form) is a possible though not a proven practical solution.

REFERENCES