Thermoplastic Recording

W. E. GLENN
General Electric Research Laboratory, Schenectady, New York
(Received January 5, 1959)

A new method is described for recording electrical signals. Information is written at extremely high density by means of an electron beam on a film consisting of a low melting thermoplastic material. This can be projected as a full color image, or can be converted to an electrical signal. The tape, which is processed by quick heating, can be readily erased and reused.

INTRODUCTION

A WIDE band width recording technique will be described in this paper in which an electron beam is used to cause deformations in the surface of a thermoplastic film. These deformations can be detected optically, and by using a special optical system described in a previous paper,[1] full color images can be projected from the film. The film requires no chemical processing and can be erased and reused. The resolution is comparable to that of photographic film and the bandwidth capability is well in excess of that required for video-recording.

RECORDING TECHNIQUE

The recording principle is illustrated in Fig. 1. The film used consists of a high-melting base film coated with a transparent conducting coating with a thin film of a low-melting thermoplastic on its surface. An electron beam is used to lay down a charge pattern on the surface of the thermoplastic film in accordance with the information to be stored. The film is then heated to the melting point of the thermoplastic. Electrostatic forces between the charges on the film and the ground plane depress the surface where the charges occur until these forces are in equilibrium with the surface tension restoring forces. The film can now be cooled below its melting point and the deformations will be "frozen" into the surface. With some materials the charge pattern will persist for days. It is usually not necessary to develop the deformations immediately after charging the film; however, this is usually done so that the recorded information can be monitored as it is being recorded.

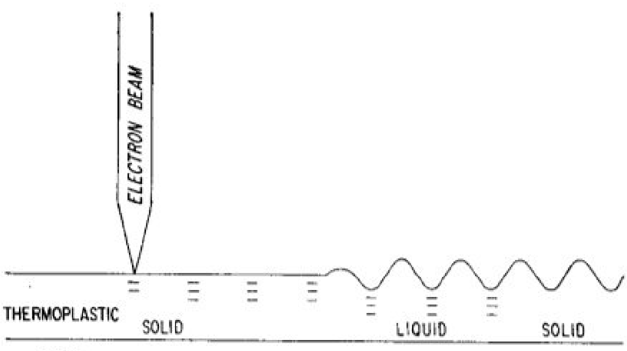

FIG. 1. Basic mechanism of thermoplastic recording.

[1] W. E. Glenn 48, 841 (1958).

The time required for the deformations to form depends on the viscosity of the film when it is melted but is usually of the order of a few milliseconds.

To erase the film the charge pattern must be discharged by heating the film well above its melting point so that its conductivity will increase. Surface tension will then smooth out the deformations and the film is ready for reuse. The film is usually heated for developing the deformations in a vacuum. It must also be cooled back below the melting point before it can be rolled up. A practical way to do this is to heat only the top surface of the film by inducing current in the transparent conducting coating for about 0.01 sec. This is ample time for the deformations to form. The heat will then diffuse into the film base and the surface will cool. By confining the rf fields, local erasure of areas a few mils square is possible if desired.

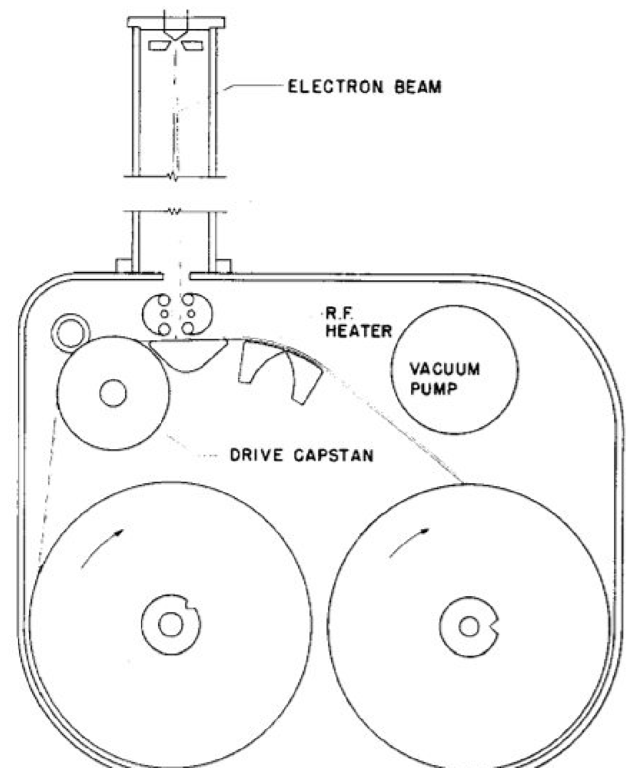

FIG. 2. Experimental thermoplastic tape recorder.

A recorder was constructed as illustrated in Fig. 2. The film plays off a reel, is driven at constant speed by a drive capstan and is charged by the electron beam. The electron beam is modulated by the signal to be recorded. The charge pattern is laid down in a television-type raster. The electron beam sweeps across the film, providing the horizontal sweep of the raster. Vertical sweep, along the film, is provided by the tape motion. As the film passes over the pair of rf electrodes, the surface is heated to the melting point of the thermoplastic, allowing the deformations to form. As the film moves on, the heat diffuses into the film base and the deformations are frozen into the surface. A small optical system, to be described later, is placed just after the rf electrodes (not shown in Fig. 2) so that the recorded information can be monitored. The entire device is in a continuously pumped vacuum chamber at a pressure of about 0.1 μ.

The charge pattern has been laid down successfully in air simply by dragging a fine wire, with the voltage to be recorded applied to it, across the surface of a thermoplastic film. However, recording in a vacuum seems to be much more practical since it permits higher writing density and speed, and is more reproducible.

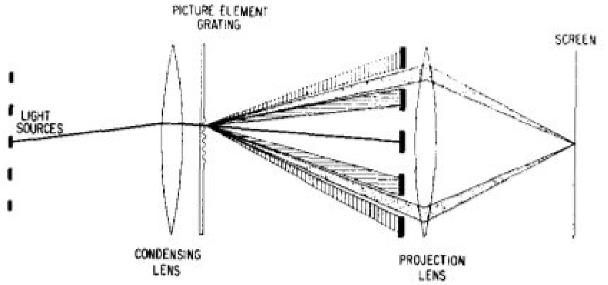

FIG. 3. Optical system for projection of color images from deformed transparent medium.

READING

(a) Color Images

For color imaging the deformations are impressed on the thermoplastic surface in the form of phase diffraction gratings. The optical system described in a previous paper[1] permits projection of a color image from such a pattern of gratings. This system is illustrated in Fig. 3. In this projector a condensing lens near the film images an array of line light sources on a set of opaque bars in front of the projection lens. Where the film is smooth, these bars intercept the light and these areas appear black on the screen. In an area where the deformations form a diffraction grating, light will be diffracted through the slots and the projection lens will image this light at a position on the screen corresponding to the position of the grating. The slots are narrow enough to admit only one primary color of the spectrum that falls on the bar system. The spacing of the grating determines the color of the picture element. The amplitude of the grating determines the intensity of the diffracted light.

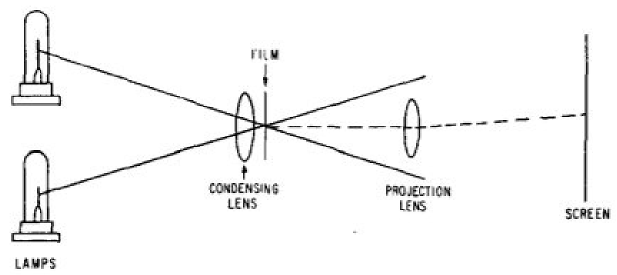

FIG. 4. Simplified optical system for case of small grating spacing (large diffraction angle).

For color image reproduction more than one primary color is necessary. A color which is the sum of two or more primary colors can be formed by simply superimposing two or more gratings, each with a spacing corresponding to a primary color. A new primary system[1] using one fixed and one variable color is found to have many advantages over a system of three fixed color primaries.

A special electron gun, to be described later, is used to produce the gratings in each picture element with the appropriate spacing and amplitude.

(b) Black and White Images

The optical system employed for projection of black-and-white pictures is a modified Schlieren system. The slots and light sources are made wide enough for the entire spectrum to be passed by the optical system. The electron beam simply scans a normal television line, depositing charge in accordance with the light intensity of each picture element. The amount of charge will govern the depth of the resulting deformation, and upon projection the light intensity of the picture element will depend upon this depth.

(c) Resolution

The electron beam size can resolve wavelengths smaller than the wavelength of light. However, the resolution of the system is limited by optical considerations. For the black-and-white system each line can be resolved by the optical system. For color, narrower slots and light sources are used. Because of diffraction from these narrower slots, about four grating lines are required to produce a resolvable picture element in color. This means that a picture element recorded in color requires about four times the area of the corresponding element recorded in black and white.

As the grating spacing is narrowed, the diffraction angle of course increases. When the diffraction angle is large, the optical system of Fig. 3 simplifies to that shown in Fig. 4.

(d) Electrical Signal Output

To read the film to produce an electrical output, a flying spot scanner or camera tube may be used with the optical system described above. A simple version of

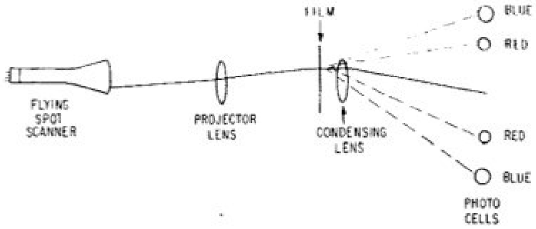

FIG. 5. Flying spot scanner optical system for converting recorded image to electrical signal.

a flying spot scanner reading system is shown in Fig. 5. Here the film is scanned with light of a single color from the flying spot scanner. Photoelectric cells are placed at different angles to accept light diffracted by gratings of different spacing.

(e) Analog or Digital Data

To record electrical signals in analog form, the electron beam is modulated by the signal to be recorded. For a single beam, the intensity can be modulated. When the split beam is used, both the grating spacing and the intensity can be modulated.

For binary digital data, a single split beam may be used. In this case, it is desirable to use only two colors, one for the 0's and another for the 1's. In this way all data bits appear as the presence of a single color. Since a dust speck scatters light randomly, it appears as white light. A coincidence in the zero and one detectors can thus be made to reject dust. Coordinate data can be recorded as the absence of a color. Since coordinates can be recorded in with the data, high mechanical tolerances are not required to realize the high resolution of the system.

ELECTRON GUN DESIGN

A special electron gun was designed which lays down a charge pattern that will form a diffraction grating of appropriate amplitude and spacing in each picture element.

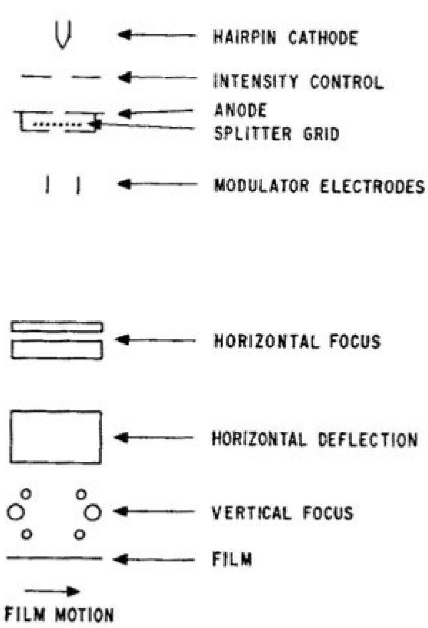

FIG. 6. Schematic drawing of electron beam splitting gun.

For recording color pictures on film, the electron beam is split into several beamlets, whose amplitude and separation can be determined by potentials applied to appropriate electrodes in the electron gun. This split beam forms the diffraction grating in each picture element. The superposition of two such multiple beams, one of fixed spacing, the other of variable spacing, but both of controllable intensity, creates the gratings required for fixed and variable color primaries. It is also possible, using a slightly different optical system, to project color images from patterns laid down with a single split beam. A schematic drawing of the electron beam-splitting gun is shown in Fig. 6.

The beam emerges from the point of the hairpin cathode, and is accelerated by the field between cathode and anode. A fine wire splitter grid, slightly positive with respect to the anode, is placed in the electron beam. Electric field lines terminating on the grid wires deflect

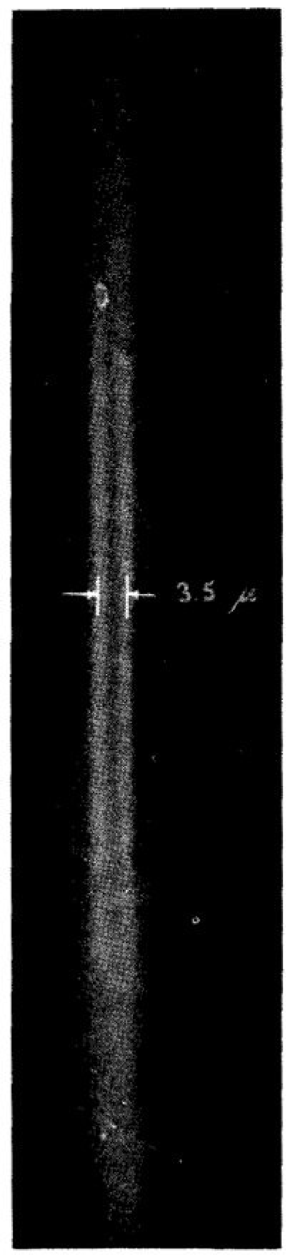

FIG. 7. Photographic image of split beam on phosphor.

different portions of the beam by a discrete amount for all electrons passing between two wires. This creates a row of apparent sources back of the wire grids. Their separation depends upon the potential of the splitter grid, thus controlling the color of the picture element. The intensity of the element is controlled by either modulating the beam current or the focus of the grating. The average splitter grid potential is chosen such that the bundles of electrons intersect in the middle of a vertical focusing cylindrical lens. This lens focuses the beamlets in the vertical direction into a row of lines on the film. Focus and deflection in the horizontal direction is provided by another cylindrical lens and set of deflection plates. Since high resolution but no deflection is required in the vertical direction there is a considerable advantage in focusing in the two directions separately.

For alignment and focus of the gun a transparent phosphor plate replaces the film. A photograph of the split beam trace on the phosphor is shown in Fig. 7. In the photograph the defocusing at the ends of the trace was due to curvature of field of the microscope objective. The split trace was in focus for a deflection length of about $1\frac{1}{2}$ in.

A photograph of raster lines recorded on thermoplastic tape with a split electron beam is shown in Fig. 8. Each raster line is split into five grating lines spaced $10\,\mu$ center to center. In the photograph the last grating line of one raster line overlaps the first grating line of the adjacent raster line to produce the heavier lines.

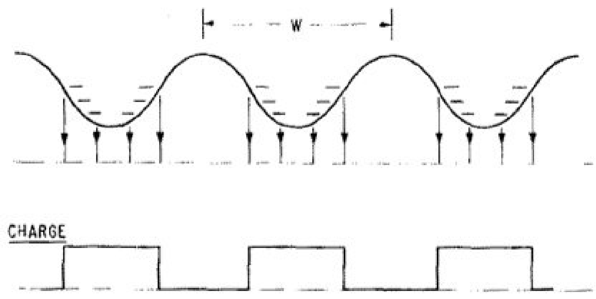

FIG. 9. Assumed deformation of thermoplastic surface (upper) and distribution of charge on surface (lower).

SENSITIVITY

An approximate expression for the current density in amp/cm² required to produce a deformation on an insulating liquid of wavelength W and depth A in centimeters can be derived as

$$i=\frac{8\times10^{-10}}{Wt}(\epsilon TA)^{\frac{1}{2}},$$

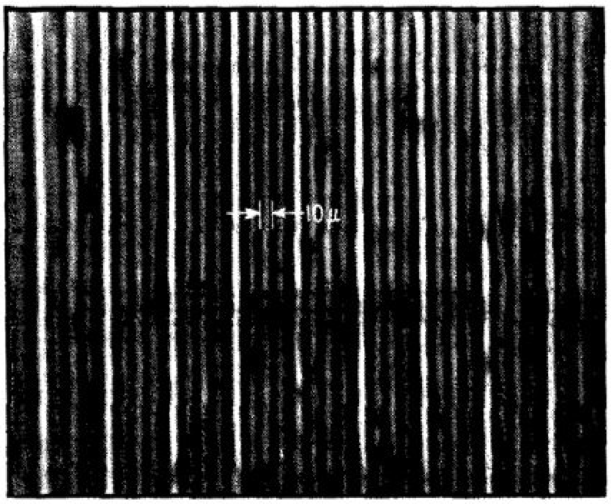

FIG. 8. Photograph of raster lines, recorded on thermoplastic tape, with split electron beam.

where ϵ = dielectric constant, T = surface tension in d/cm, t = dwell time of spot in seconds. This expression was derived by equating the electrostatic forces produced by the charge pattern to the restoring forces. The restoring forces consist of hydrostatic pressure in the liquid (the means by which the force on the surface is transferred to the base) and surface tension forces. The following simplifying assumptions were made (see Fig. 9): (a) The profile of the ripple can be represented by a pair of parabolas; (b) the charge is deposited on the surface in a square wave of wavelength W; (c) the field lines are essentially parallel. To diffract maximum light of wavelength λ into the first order the approximate value for $A=(\lambda/2(n-1))$ where n is the index of refraction. If visible light is used, the product ϵTA is about 25×10^{-4} for most thermoplastics and oils. The above expression is then typically $i=(4\times10^{-11})/Wt$. This expression has been confirmed experimentally for both oils and thermoplastics and found to be correct within a factor of two. About $\frac{1}{2}$ amp/cm² is required to write video band widths with a 10-μ grating spacing. This is far below the current density available from the electron gun.

When the depth of penetration of the writing electrons is an appreciable fraction of the wavelength W, the expression is not believed to hold. At 15-kv beam energy the grating amplitude drops rapidly below $10\,\mu$ even though the electron beam resolution is much better than this. To reach the ultimate resolution limit of the optical system with reasonable current densities the depth of penetration of the electron beam must be reduced. The foregoing expression does not depend markedly on the wave shape of the deposited charge pattern, or film thickness. However, because of several practical considerations it is preferable to use a film thickness of about one-half the grating spacing.

ACKNOWLEDGMENTS

The author would like to acknowledge the contribution of Dr. E. M. Boldebuck and her colleagues of the Chemistry Department of this Laboratory for developing thermoplastic materials. The assistance and suggestions of Mr. J. L. Henkes have been valuable in all phases of this work.