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Collins et al.

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[54] **RASTER PATTERN MAGNETORESISTORS**

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Related U.S. Application Data

[63] Continuation-in-part of Ser. No. 748,069, July 26, 1968, Pat. No. 3,592,708.

[52] **U.S. Cl.** ..... **117/212,** 117/217, 338/32 R, 338/32 A

[51] **Int. Cl.** **B44d 1/18,** C23b 5/50

[58] **Field of Search** ..... 117/212; 338/32 R, 32 A

[56] **References Cited**

UNITED STATES PATENTS

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Attorney, Agent, or Firm—Richard S. Sciascia; Joseph M. St. Amand

[57] **ABSTRACT**

A thin-film raster pattern magnetoresistor device produced from an electron beam-recrystallized InSb film employing a photolithographic process to etch out of the InSb film a suitable pattern on which micron-size indium or copper stripes are later etched from a superposed metallic film applied on the InSb by vacuum deposition. The thin-film raster pattern magnetoresistor device is a resistor, whose initial resistance in zero magnetic field is between 10 and 1,000 ohms, and whose resistance increases with an applied magnetic field, reaching a value greater than a factor of 10 on the initial resistance in a magnetic field of 10 kOe.

3 Claims, 2 Drawing Figures

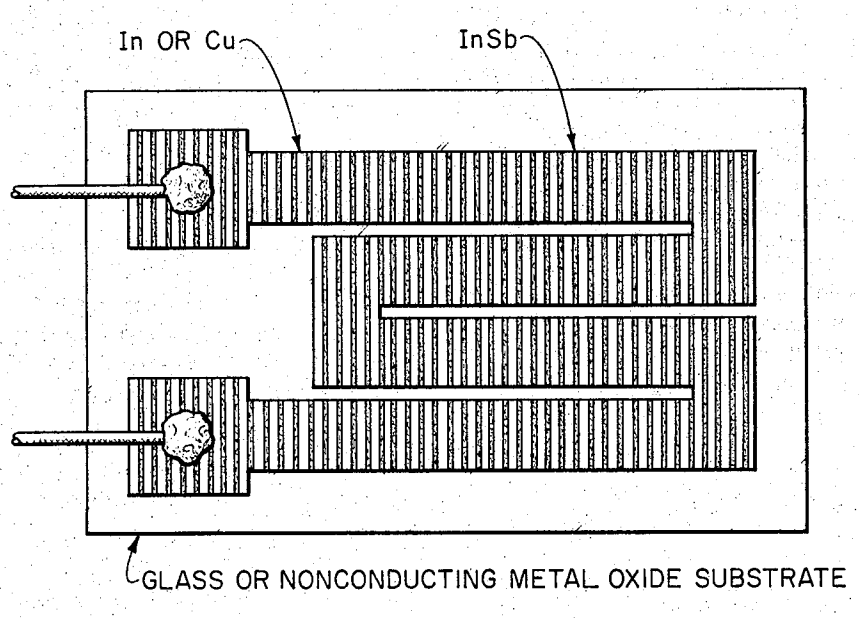


Fig. 1.

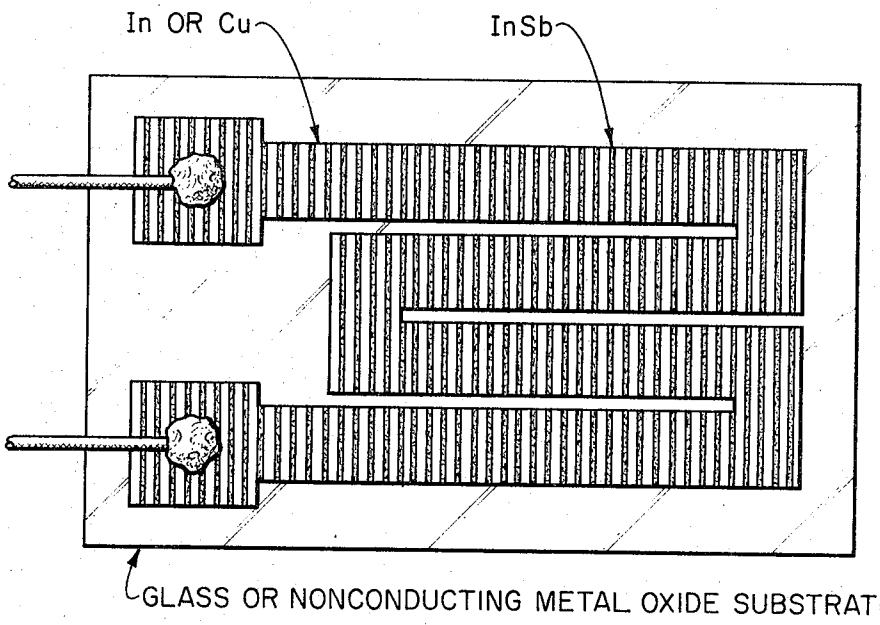
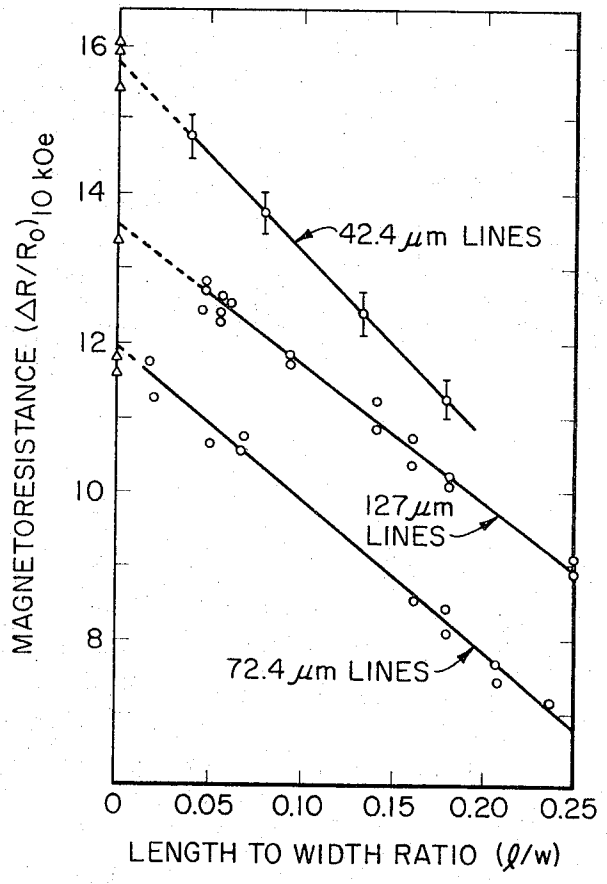

In OR Cu
InSb
GLASS OR NONCONDUCTING METAL OXIDE SUBSTRATE

Fig. 2.


MAGNETORESISTANCE $(\Delta R/R_o)_{10\ kOe}$
16
14
12
10
8
42.4 μm LINES
127 μm LINES
72.4 μm LINES
0
0.05
0.10
0.15
0.20
0.25
LENGTH TO WIDTH RATIO (ℓ/w)

RASTER PATTERN MAGNETORESISTORS

This application is a continuation-in-part of U.S. Pat. application, Ser. No. 748,069 filed July 26, 1968 for Method of Making Raster Pattern Magnetoresistors, now U.S. Pat. No. 3,592,708.

The invention herein described may be manufactured and used by or for the Government of the United States of America for governmental purposes without the payment of any royalties thereon or therefor.

This invention is concerned with the specific electrical and galvanomagnetic properties of raster pattern thin film magnetoresistors.

A magnetoresistor is a two-terminal device whose resistance is a function of the transverse magnetic field. Its resistance can be varied slowly or fast, synchronously or asynchronously by varying the magnetic field of an electromagnet acting upon it.

Raster pattern magnetoresistors employing a bar of bulk-crystalline indium antimonide have several shortcomings: (a) while the magnetic sensitivity is very large, the zero field resistance is quite small, i.e., of the order 1 to 10 ohms. This is due to the difficulty of grinding a specimen to the small dimensions needed without breaking it; (b) it is difficult to reduce the size of bulk magnetoresistors to microscopic dimensions. This is desirable in order to focus the magnetic flux generated by a permanent magnet or an electromagnet by means of suitably shaped ferromagnetic pole pieces which concentrate the magnetic flux onto a small area from a broader source, i.e., $\Phi = BA$ where Φ is the magnetic flux, A is the cross-sectional area of the tip of the flux concentrater and the magnetic induction $B = \mu H$ where μ is the permeability of the flux concentrater; (c) it is difficult to fabricate complex shapes of magnetoresistors, such as for providing different changes in existance for the same amount of mechanical displacement of a permanent magnet acting on the magnetoresistor. This is desirable if the magnetoresistor is to act as a transducer of complex mechanical motion in two dimensions; (d) a further disadvantage of bulk raster pattern magnetoresistors is the effect of the electrodes. In a relatively thick device employing bulk indium antimonide the electric current stream lines do not effectively short the Hall field due to the fact that the current stream lines are not everywhere perpendicular to the magnetic flux lines. In the thin-film magnetoresistor the situation is improved considerably; (e) a further disadvantage of bulk indium antimonide magnetoresistors is that the dissipation of heat by thermal conduction is a serious problem due to high temperature coefficient of resistance of InSb. In thin film magnetoresistors this large surface to volume ratio provides an effective method for best dissipation and consequently a smaller rise in temperature gives the same environmental conditions and the same input current, in comparison with bulk InSb magnetoresistors.

These disadvantages can be overcome by the thin film magnetoresistors of this invention.

The purpose of the invention is the production of a resistor whose value is a function of the applied magnetic field, i.e., magnetoresistors. Materials best suited for the construction of magnetoresistors are the intermetallic compounds InSb and InAs. In order to produce high sensitivity magnetoresistors, i.e., devices whose resistance shows a strong variation with magnetic field, the Hall voltage generated in the semiconducting material (InSb or InAs) must be short circuited. This can be accomplished by an actual physical short circuit of the electrodes, such as in a Corbino disc, with the electrodes disposed in a coaxial fashion, or alternatively, conductive lines applied to a rectangular device can be used to produce an electrostatic short circuit. Still another procedure is the introduction of metallic inclusions into the semiconductor; however, for best results these inclusions should be arranged in a highly directional manner and should have a needle-like shape. This orientation should be normal to the applied magnetic fields and current. Magnetoresistors made of bulk InSb have a higher magnetoresistance ($\Delta R/Ro$) than thin film magnetoresistors. However, their effective resistance R(H) is small, at most a few hundred ohms. In many applications it is desirable to have the effective resistance R(H) of the order of thousands of ohms. This can best be done by means of thin film magnetoresistors.

Thin film magnetoresistors made of the two-phase system InSb and In, i.e., InSb with In inclusions, have a relatively high magnetoresistance. It is difficult, however, to control their impurity concentration. The latter determines the ultimate temperature sensitivity of the devices. It is also difficult to produce reproducibly the same effective resistance R(0) and magnetoresistance ($\Delta R/Ro$).

The advantages of the present invention are: Higher quality InSb recrystallized by an electron beam microzone process can be produced under reproducible and controlled conditions (Donor impurities can be introduced into the film in accordance with copending U.S. Pat. application, Ser. No. 747,511 filed July 25, 1968 by Harry H. Wieder and Arthur R. Clawson for Sulfur Doped Recrystallized InSb Films) now U.S. Pat. No. 3,591,429; A metallic high density, line-raster pattern can be used to cover the films in order to obtain a specific desired magnetoresistance ratio in terms of the length to width ratio of the InSb segment included between two raster lines; The effective magnetoresistance ($\Delta R/Ro$) is that of the (near perfectly) short circuited InSb segment and can be used as a design criterion for various magnetoresistor configurations on either flat or curved substrates.

Other objects and many of the attendant advantages of this invention will become readily appreciated as the same becomes better understood by reference to the following detailed description when considered in connection with the accompanying drawings wherein:

FIG. 1 is an illustration of a typical magnetoresistor made of electron beam microzone-crystallized InSb film covered by an In or Cu film raster pattern.

FIG. 2 shows magnetoresistance ($\Delta R/Ro$) as a function of the magnetic field H for various length to width (l/w) ratios of raster pattern lines.

The galvanomagnetic properties of 3 to 5 μm thick InSb films grown by electron beam microzone synthesis and crystallization of composite vacuum deposited (In + Sb) layers are essentially the same as those of bulk InSb with a comparable impurity concentration. The magnetic field and geometry dependence of the magnetoresistance ($\Delta R/Ro$), of raster plate magnetoresistor configurations made of such films have been investigated. A large transverse ($\Delta R/Ro$) is to be expected from a series-connected array of identical InSb parallelipipeds whose thickness is slight with respect to their other dimensions and whose main surfaces are covered by metallic electrodes. A somewhat smaller ($\Delta R/Ro$)

can be obtained by vacuum depositing or electroplating a raster of metallic lines on an InSb plate in such manner that the InSb strips included between the lines have a small length to width (l/w) ratio in the direction of the applied current.

Photolithographic techniques are used to construct typical raster pattern InSb film magnetoresistors such as the one shown in FIG. 1. Indium films 0.5 μm in thickness are vaccum deposited on electron beam-crystallized InSb films deposited on glass or pyrex substrates. A raster pattern of identical lines is then etched out of the In film by means of an etchant which attacks preferentially the In film but not the underlying InSb layer (a suitable etching solution is H_3PO_4—H_2O_2 in a 40:1 ratio held at a temperature of +80°C.) The magnetic field and geometry dependence of ($\Delta R/Ro$) of such raster plates is similar to that of single crystal InSb dendrites; magnetoresistance ($\Delta R/Ro$) is proportional to the square of the magnetic field, H^2, up to ~ 2 kOe and is linear in magnetic field H above 3 kOe. It increases with the electron mobility, μ_n and with the increasing density of the In lines, i.e., with a decrease in the (l/w) ratio.

FIG. 2 shows that the magnetoresistance ($\Delta R/Ro$) of raster pattern magnetoresistors such as shown in FIG. 1 is a linear function of length to width (l/w) ratios of raster pattern lines for (l/w) $\leq$ 0.2, T = 296°K and H = 10 kOe. Width of the metallic lines is identical to spacing between lines. The thickness d and the galvanomagnetic coefficients of the respective InSb films are: 42.4 μm film, $d = 4.05$ μm, $n = 6 \times 10^{16}$ cm^{-3}, $\mu_n = 4.7 \times 10^4$ cm^2/Vs and $\rho = 2.21 \times 10^{-3}$ ohm-cm; 127 μm film, $d = 3.06$ μm, $n = 2.4 \times 10^{16}$ cm^{-3}, $\mu_n = 4.2 \times 10^4$ cm^2/Vs and $\rho = 6.19 \times 10^{-3}$ ohm-cm; 72.4 μm film, $d = 1.02$ μm, $n = 5.2 \times 10^{16}$ cm^{-3}, $\mu_n = 3.3 \times 10^4$ cm^2/Vs and $\rho = 3.64 \times 10^{-3}$ ohm-cm. Average values of ($\Delta R/Ro$) and standard deviations are shown for nine specimens of 42.4 μm raster magnetoresistors. Triangular points on ordinate represent Corbino disc magnetoresistance measured in H = 10 kOe. Corbino disc configurations, made of InSb films with the same thickness, electron mobility and donor concentration as those of corresponding raster pattern magnetoresistors, are shown in FIG. 2 to have ($\Delta R/Ro$) in fair agreement with the extrapolated ($\Delta R/Ro$) vs (l/w) function to (l/w) = 0. In contrast with two-phase (InSb + In) ordered dendritic film magnetoresistors which exhibit an anomally in the temperature dependence of ($\Delta R/Ro$) because of the anomalous temperature dependence of μ_n, raster pattern magnetoresistors have been found to be independent of temperature between 296°K and 77°K to within 2.3 percent.

An advantage of film over bulk magnetoresistors is their high resistance per film surface area. Small surface areas are desirable in order to obtain a high effective magnetic induction, by focusing an applied magnetic flux, by means of flux concentrators, onto a magnetoresistor. The large surface-to-volume ratio also provides for an efficient thermal dissipation of Joule heat from the body of a magnetoresistor to its surroundings. In contrast with bulk devices, film magnetoresistors can be processed into complex shapes on either plane or curved substrates. They can also be made in non-inductive configurations such as required for high frequency applications.

Exact theoretical solutions for the geometry-dependent transverse ($\Delta R/Ro$) have been developed they are based on a conformal representation of the electric field distribution in rectangular plates. Approximate theoretical solutions have also been devised using finite difference equations to solve Laplace's equation in two dimensions. In each case, it is assumed that the medium is homogeneous and isotropic, that (in H = 0) the current streamlines emerge normal to the equipotential electrodes, that the constraints $\nabla \times \bar{E} = 0$, $\nabla \cdot \bar{J} = 0$ and $\bar{E} = -\nabla \Phi$ are applicable, and that the resistivity acquires a gyrotropic character in an applied magnetic field. Here $\bar{E}$ is the electric field, Φ the scalar potential and $\bar{J}$ the current density vector.

Considering a raster plate in a Cartesian coordinate system, the indium electrodes are in the xy-plane, parallel to the InSb film surfaces. The current density vector $\bar{J}$ has J_x as well as J_y and J_z components. The electric field distribution in the presence of a magnetic field is:

$$(\delta^2\Phi/\delta x^2) + (\delta^2\Phi/\delta y^2) + (1 + \tan^2\theta)(\delta^2\Phi/\delta z^2) = 0 \quad (1)$$

where $\theta = \mu_n H$, is the Hall angle. A charge density σ_c is present such that

$$\sigma_c = \tan^2\theta \cdot (\delta^2\Phi/\delta z^2)/4\pi \quad (2)$$

Only if $\sigma_c = 0$ is the two-dimensional solution of Laplace's equation applicable.

The results of a resistance-paper analog plot made of the potential distribution along the cross-section of a raster plate in the vicinity of an electrode indicated that only for $x < d$ are the equipotentials a function of z. For $x > d$ the current streamlines and equipotentials behave as if the electrodes were effectively normal to the film surfaces and the two-dimensional solution of Laplace's equation is applicable in the fractional film volume $(1 - \epsilon)$ where $\epsilon \approx 2d/l$. The experimentally measured ($\Delta R/Ro$) should agree with the theoretically derived expressions for the (l/w) and tan θ dependence of ($\Delta R/Ro$), provided that $\epsilon << 1$. FIG. 2 shows that for a raster plate containing 42.4 μm wide stripes, ($\Delta R/Ro$) = 4.7×10^4cm^2/Vs. The theoretically derived geometry dependent magnetoresistance in the high field region for (l/w) = 0.2 is:

$$(\Delta R/Ro) = (w/l\,[\mu_n H + g\,(l/w)] - 1 \quad (3)$$

the function $(w/l) \cdot g(l/w) \approx -11$; thus for magnetic field H = 10^4Oe, ($\Delta R/Ro$) -11.5. The small discrepancy between the calculated and measured ($\Delta R/Ro$) is not unreasonable in view of the fact that ($2d/l$) ≈ 0.19. Similar results have also been obtained on the other magnetoresistors. High raster line densities are desirable in order to decrease the (l/w) ratio and thus to increase the magnetic field sensitivity, $\delta(\Delta R/Ro)/\delta H$ of magnetoresistors, as well as for increasing their effective resistance per unit surface area. A raster consisting of 1 μm In lines is well within the resolution attainable at the present time by means of standard photolithographic techniques. However, the distortion of the equipotential lines can be significant and lead to a reduction in ($\Delta R/Ro$) unless the film thickness d is also reduced. A reduction in film thickness to less than 1 μm does not appear desirable since there is a sharp re-

duction in μ_n with d which may be due to scattering of electrons from the film surfaces.

The photolithographic process used to produce raster pattern InSb film magnetoresistors consists of several steps as follows: First, a chemical photoresist coating (e.g., AZ-1350 Shipley Co. Inc., Los Angeles, Calif.) is applied to a previously processed InSb film, on a glass substrate, grown by electron beam microzone synthesis and crystallization. Then a particular magnetoresistor pattern mask is superposed on the coated film and the slide assembly is exposed to ultraviolet light. The exposed photoresist is then removed by the use of a developer (e.g. Developer for AZ-1350 Photoresist). Chemsol D or aqua regia is then used to etch the pattern out of the InSb film, and, then the remaining photoresist is removed with acetone. Following this an indium film 0.5 to 2 μm thick is evaporated onto the entire glass substrate, including the processed magnetoresistor pattern. A photoresist coating, the same as in the first step, is again applied to the entire slide assembly. Now a raster line pattern mask is superposed on the substrate and exposed to ultraviolet light, and the exposed photoresist is then removed using a developer as aforementioned. The line pattern is then etched out by immersing the slide assembly for 2 to 5 minutes, into a 40:1 solution, for example, of H_3PO_4—H_2O_2 held at a temperature of 80°C; and the remaining photoresist is removed with acetone. The indium film does not adhere to the bare glass in the hot etching solution just described; nor does the etchant attack the InSb film, only the exposed In lines of the In raster pattern. Thus a raster of In lines is left on the InSb magnetoresistor pattern (FIG. 1.).

The glass substrate surrounding the magnetoresistor pattern is cut away, for example, by means of a stream of abrasive particles propelled by a nitrogen jet, such as an S.S. White Airbrasive Unit. Electrodes of the magnetoresistor can be Copper electroplated and leads can be attached by soldering or by the use of a conductive epoxy cement.

Other semiconducting films such as InAs or ternary compound films such as $InSb_xAs_{1-x}$ can be produced by chemical vapor phase transport procedures.

Obviously many modifications and variations of the present invention are possible in the light of the above teachings. It is therefore to be understood that within the scope of the appended claims the invention may be practiced otherwise than is specifically described.

What is claimed is:

1. A high sensitivity raster pattern magnetoresistor device whose resistance shows a strong variation with magnetic field, comprising:

a. a non-conducting substrate,

b. an electron beam microzone-crystallized semiconducting thin film having microscopic thickness of from 3 to 5 μm and selected from the group of intermetallic compounds consisting of InSb and InAs in a magnetoresistor pattern formed on said substrate;

c. a high density raster pattern of identical metallic lines of microscopic thickness on the surface of said conducting thin film, said raster pattern of metallic lines together with said semiconducting thin film providing a series-connected array of identical semiconductor parallelipipeds whose thickness is slight with respect to their other dimensions such that the semiconducting film between the metallic lines has a small length to width ratio in the direction of applied current and the width of the metallic lines is identical with the spacing between said lines;

d. said metallic lines being of the order of 0.5 to 2.0 μm in thickness;

e. the initial resistance of said magnetoresistance device being between 10 and 1,000 ohms which resistance increases with an applied magnetic field reaching a value greater than a factor of 10 of the initial resistance in a magnetic field of 10 kOe, said magnetoresistor also having a large surface-to-volume ratio which provides for efficient thermal dissipation of heat from the body of said magnetoresistor to its surroundings.

2. A high sensitivity magnetoresistor device as in claim **1** wherein said metallic lines are In.

3. A high sensitivity magnetoresistor device as in claim **1** wherein said metallic lines are Cu.

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