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(54) **An FeGaSi-based magnetic material with Ir as an additive.**

(57) A magnetic material comprised of FeIrGaSi, containing Ir at a concentration of 1.0 to 4.0 atomic percent, has improved high-frequency permeability and wear resistance and an elevated Curie temperature. Furthermore, FeIrGaSi has a uniaxial anistropy property of several Oersteds induced by magnetic annealing of sputtered FeIrGaSi in thin film form at temperatures between 350 and 600°C.

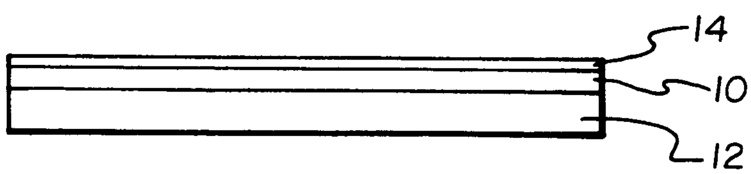

FIG. 1

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1. Field Of The Invention

The present invention relates to a magnetic material suitable for high-density magnetic recording. More specifically, the invention relates to a magnetic head material for high-density recording.

2. Description Of The Prior Art

There is an increasing demand for large capacity, high transfer rate recording apparatus, for both image and data storage. Increased capacity requires narrow recording tracks and high linear recording densities. In order to increase linear density, high-coercivity recording media, like metal particle or metal evaporated, are needed. In turn, higher saturation magnetization is needed in the magnetic material used for the record head core. A high transfer rate, on the other hand, demands faster head-to-media velocity coupled with higher recording frequencies. Higher recording frequencies put additional demands on the record head material.

Monolithic ferrite has been a material for record heads used in both magnetic disk and tape drives when the coercivity of the recording medium is less than 700 Oersteds (Oe) and the highest frequency is about ten megahertz (MHz). However, due to the need for higher saturation magnetization and high frequency response, ferrite is not a good choice for newer applications.

Historically, permalloy (NiFe) has been the magnetic material of choice for a record head of the thin film type. However, NiFe has poor wear resistance, and has a relatively low resistivity, causing permeability to decrease rapidly for higher frequencies due to eddy current losses.

Relative to monolithic ferrite, a sputter-deposited Sendust (FeSiAl) alloy film offers a higher saturation magnetization, about 10 kilogauss (kG). Furthermore, a Sendust alloy has a relatively high resistivity and good wear resistance.

More recently, however, FeGaSi has been disclosed as a crystalline magnetic alloy having, compared to Sendust, both a higher saturation magnetization (about 13 kG) and lower coercivity (about 0.1 Oe). (See Journal of Applied Physics, Vol. 61, No. 8, pages 3514 through 3519.) However, FeGaSi alloy films suffer from a disadvantage in that their permeability, although almost constant in a range from 1 to 10 MHz, decreases rapidly for higher frequencies due to eddy current losses.

Following on this development, there is known in the art an FeGaSi-based alloy film having Ru as an additive. FeRuGaSi has a high saturation magnetization, although somewhat lower than FeGaSi, and an excellent soft magnetic property (low coercivity) suitable for recording in a high frequency range near 100 MHz. (See Journal of Applied Physics, Vol. 64, No. 2, pages 772 through 779.) However, FeGaSi, in addition to its high-frequency permeability problem, and FeRuGaSi both suffer from a disadvantage in that they lack a meaningful uniaxial anisotropy characteristic. Without uniaxial anisotropy, the construction of a thin film or multilayer (laminated) head with an easy axis of magnetization orthogonal to magnetic flux in the pole tip area is not possible. Such a domain wall configuration is desirable because it improves head efficiency, in particular at high frequencies, since magnetization reversal near the pole tips occurs mainly by rotation rather than by domain wall movement.

SUMMARY OF THE INVENTION

In view of the foregoing, an object of the invention is to provide a magnetic head material without the disadvantages of the prior art in that the head material has both a high saturation magnetization and a high permeability at high frequencies, and is readily suitable as the core material for thin film or laminated magnetic heads. This object is achieved by an FeIrGaSi soft magnetic thin film having a uniaxial magnetic anisotropy of several Oersteds, induced by magnetic annealing of sputtered FeIrGaSi in thin film form. In a presently preferred embodiment, FeIrGaSi, in accordance with the invention, is produced initially in sputtered form, with Ir at a concentration level of 1.0 to 4.0 atomic percent, by simultaneously sputtering from an Fe-rich FeGaSi target and an Ir target. After sputter deposition, uniaxial anisotropy is induced by annealing the as-sputtered alloy film in a magnetic field at temperatures between 350 and 600°C in steps of either 25 or 50°C. Prior to annealing, however, a protective layer of SiO_2, deposited on the as-sputtered alloy by an RF reactive sputtering method, serves to protect the alloy film from oxidation during annealing.

The advantages of the invention will become apparent in the detailed description of a preferred embodiment presented below.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention will be described with reference to the accompanying drawings, wherein:

Fig. 1 is a sectional view showing a film of FeIrGaSi in accordance with the invention;
Fig. 2 is a schematic drawing of apparatus for sputter deposition of an alloy film; and
Figs. 3 through 6 are graphs and data illustrating advantages of the present invention.

DESCRIPTION OF THE INVENTION

In order to have a high linear recording density, two magnetic head material parameters are of particular importance: saturation magnetization and high-frequency permeability. An FeGaSi alloy film, whose composition is $Fe_{77}Ga_9Si_{14}$ (atomic percent), is known from the aforementioned Journal of Applied Physics, Vol. 61, No. 8, to have high saturation magnetic induction and soft magnetic properties, although permeability does decrease rapidly for higher frequencies due to eddy current losses.

I have found, however, that by adding a small quantity of iridium (Ir) to FeGaSi, several important magnetic properties are improved relative to the magnetic properties of the base alloy FeGaSi. For example, small additions of Ir (up to about four (4) atomic percent) to $Fe_{79}Ga_6Si_{15}$ create an FeIrGaSi film having, compared to the base alloy, improved soft magnetic properties, increased wear resistance, and an elevated Curie temperature. A further important advantage is that FeIrGaSi, after appropriate magnetic annealing, has, unlike FeGaSi, a uniaxial anisotropic characteristic of several Oersteds.

An FeRuGaSi alloy film, whose typical composition varies between $Fe_{72}Ru_4Ga_7Si_{17}$ and $Fe_{68}Ru_8Ga_7Si_{17}$ (atomic percent), is also known in the art to have a relatively high saturation magnetic induction, and excellent soft magnetic properties, although FeRuGaSi, like FeGaSi, lacks a uniaxial anisotropic characteristic. I have also found, as described in detail hereinbelow, that FeIrGaSi, compared to FeRuGaSi, has a much higher permeability, a smaller coercivity (softer magnetic property), and a higher Curie temperature.

Fig. 1 shows generally a thin film 10 of FeIrGaSi, in accordance with the invention, formed on a ceramic substrate 12 by a DC sputtering technique. After sputter deposition to a thickness of approximately 2μ, uniaxial anisotropy is induced by magnetically annealing the alloy film in a magnetic field of 250 Oe, at temperatures between 350 and 600°C in steps of either 25 or 50°C. To that end, a layer of silicon dioxide (SiO_2) 14, deposited prior to annealing by means of an RF reactive sputtering method to a thickness of approximately 1000 angstroms, serves to protect the alloy film from oxidation during annealing.

Fig. 2 shows apparatus 16 for depositing the FeIrGaSi thin film 10 by sputtering. For that purpose, a sputtering chamber 18 includes an electrically conductive holder 20 to which a substrate 22, preferably silicon, is secured. The aforementioned ceramic substrate 12 is secured to the substrate 22, preferably by thermal conductive grease or paste.

FeIrGaSi is produced initially in sputtered form by simultaneously sputtering from a target of FeGaSi in bulk form and a target of Ir also in bulk form. For that purpose, a vacuum-cast target 24, comprised of an FeGaSi alloy of a predetermined composition, is situated on an electrically conductive platform 26. Additionally, one or more thin sheet targets 28 of Ir are secured to the FeGaSi target 24, preferably by spot welding. The number of targets 28 and the composition of the FeGaSi target 24 are determined by the desired concentration of Ir and other elements (Fe,Ga,Si) in the resultant FeIrGaSi alloy to be formed.

In a presently preferred embodiment, the FeGaSi target is in the form of a disk having a diameter of approximately 5.7 cm and a thickness of about 0.6 cm; each Ir target is in the form of a 0.5 cm square, with a thickness of 0.25 mm. With targets of those dimensions, each Ir target 28 contributes about 1.3 to 1.6 atomic percent to the FeIrGaSi alloy formed. The targets 24 and 28 may be purchased from Mitsui Comtec Company of Saratoga, California and Morton Thiokol, respectively.

A target 30, in the form of a SiO_2 wafer disposed on an electrically conductive platform 32 inside the chamber 18, serves for sputtering the aforementioned protective layer 14 of SiO_2 onto FeIrGaSi while the latter is in its sputtered form. Shutters 34 and 36, associated respectively with the targets for sputtering FeIrGaSi and SiO_2, function, by means not shown, to allow the selection of which compound is to be sputtered.

The apparatus 16 further comprises a thermionic emitter 38 and an anode 40, to which is connected a DC power supply 42, as shown. Separate sputtering mechanisms serve to excite the combined targets 24 and 28 (FeGaSi and Ir), and the SiO_2 target 30. For sputtering FeIrGaSi, the platform 26 and the platform 20 are connected to a high-voltage DC power source such that the platform 26 is biased strongly negatively relative to the platform 20.

The sputtering mechanism for exciting the SiO_2 target 30, on the other hand, comprises an RF generator the output of which is connected to the platform 32.

In order to sputter a thin film of FeIrGaSi, a vacuum pump 46 first evacuates the chamber 18; then, argon gas is introduced into the chamber 18 through a valve 48. The argon in the chamber 18 becomes ionized when the power supply 42 applies voltage across the anode 40 and the emitter 38. The ionizing of the gas produces an argon plasma in the chamber 18.

When the shutter 34 uncovers the targets 24 and 28, positive argon ions accelerate toward the negatively biased electrically conductive platform 26, thereby simultaneously bombarding the FeGaSi target and the Ir target. This bombardment ejects atoms of the respective targets which deposit in so-called sputtered form as an alloy film of FeIrGaSi on the substrate 12. A permanent magnet 62 provides a field of a given intensity across the ceramic substrate 12 so that sputtered material is deposited in a direction that establishes an easy axis of the resultant alloy film.

When an alloy film of a desired thickness is formed, the DC power supply 42 is disconnected from the anode 40 and the emitter 38 and the shutter 34 covers the targets 24 and 28. A protective layer of SiO_2 is then deposited on the sputtered film of FeIrGaSi. For that purpose, the shutter 36 uncovers the SiO_2 target 30 and the generator 44 applies RF power to the electrically conductive platform 32. The RF generator 44 excites residual plasma in the chamber 18, and argon atoms of the plasma now bombard the target 30, thereby ejecting SiO_2 molecules which deposit on the FeIrGaSi alloy film covering the substrate 12.

A radiant lamp 66, located in the chamber 18 adjacent the substrate 12, functions as a heat source to heat the substrate 12 during RF sputtering of SiO_2. A conventional temperature-measuring device 68, such as a thermocouple, continuously monitors the temperature of the substrate 12.

The sputtering conditions for forming the thin film of FeIrGaSi and its protective layer of SiO_2 are as follows:

1.	Chamber background pressure	$2.5x10^{-7}$ Torr
2.	Argon pressure	$3x10^{-3}$ Torr
3.	DC power	300 watts
4.	FeIrGaSi deposition rate	230 A/minute
5.	SiO_2 deposition rate	11 A/minute
6.	Ceramic substrate	MnNi oxide
7.	Substrate temperature	
	DC sputtering	ambient
	RF sputtering	200°C
8.	Magnetic field	200 Oe

After sputtering is concluded, samples of the FeIrGaSi alloy film, in as-sputtered form with its SiO_2 protective film, are subjected to a magnetically annealing process to induce a uniaxial anisotropy into the alloy film. For that purpose, alloy film samples are isothermally annealed for one hour at a temperature that varies from 350°C to 600°C in steps of either 25 or 50°C. After each successive 1-hour step, the samples are cooled to room temperature. To induce unlaxial anisotropy, all anneals are done in a magnetic field of 250 Oe parallel to the field applied during deposition.

An alloy film of FeIrGaSi acquires a uniaxial anisotropic characteristic of several Oersteds after appropriate magnetic annealing of the sputtered alloy in thin film form. Uniaxial anisotropy is a very desirable property since it allows the fabrication of a multilayered or thin film inductive head with an easy axis of magnetization perpendicular to the magnetic flux in the pole tip area. Such a domain wall configuration improves head efficiency, in particular at high frequencies, since magnetization reversal near the pole tips will mainly occur by rotation rather than by domain wall movement.

Fig. 3 shows, as a function of annealing temperature, the effect of the Ir content of various FeIrGaSi films on uniaxial anisotropy. For comparison purposes, Fig. 3 also shows the uniaxial anisotropy for an FeGaSi film (78.7 Fe, 6.3 Ga, and 15.0 Si at. %) and an FeRuGaSi film (69.3 Fe, 7.9 Ru, 6.8 Ga, and 15.9 Si at. %). Each annealing step occurred in 1-hour steps and all samples were cooled to room temperature after each step before anisotropy measurements were taken. For all samples, $Fe_{74.0}Ga_{8.5}Si_{17.5}$ (at. %) was the composition of the sputter target 24 to which an additive target was combined.

As shown, all samples containing more than 1.0 at. % Ir have significantly higher uniaxial anisotropy than the FeGaSi and FeRuGaSi films after 1-hour step annealing between 350 and 600°C. The temperature stability of uniaxial anisotropy of FeIrGaSi is critical from the point of view of head fabrication processes performed at elevated temperatures such as glass bonding.

Permeability is another very important magnetic property directly affecting head efficiency. Fig. 4 shows, as a function of annealing temperature, the affect of the Ir content of FeIrGaSi on high-frequency (@150 MHz) permeability. A sample of FeGaSi and a sample of FeRuGaSi are also shown for comparison. Alloy films containing Ir generally exhibit much higher permeability than the FeGaSi and FeRuGaSi films, particularly for 1-hour step annealing between 375 and 550°C.

Coercivity is also an important magnetic property of soft magnetic materials and is inversely proportional to the initial permeability if magnetization reversal process is controlled by domain wall movement. Fig. 5 shows coercivity versus annealing temperature of various FeIrGaSi samples, with an FeGaSi and an FeRuGaSi film included for comparison. It can be seen that coercivity is generally independent of film composition and in all films remains below about 0.5 Oe after step annealing for 1 hour between 375 and 550°C. Although there is no dominant trend, coercivity is somewhat smaller in Ir-containing films.

A high Curie temperature, T_c, is desirable for a head material from the point of view of thermal stability of magnetic properties during head fabrication and subsequent usage. The T_c of various FeIrGaSi films as well as FeGaSi and FeRuGaSi films are given in the table of Fig. 6. As shown, the addition to an FeGaSi film of Ir up to about 3 at. % generally increases Curie temperature, and the T_c of an FeIrGaSi film is higher than the T_c of an FeRuGaSi film.

Wear tests of two FeIrGaSi films (containing about 1.5 and 3 atomic percent Ir) have shown that they have wear resistance better than an FeGaSi film and better than or at least comparable to an FeRuGaSi film which contains about 7.3 atomic percent Ru. Thus, small additions of Ir to FeGaSi produce the same improvement in wear resistance as a larger amount of Ru. This is another major advantage of an additive of Ir over a Ru additive since both of these non-magnetic elements when added to an FeGaSi alloy substitute for Fe atoms on lattice sites, and generally decrease magnetization saturation, M_s.

Various samples of FeIrGaSi have been investigated having Fe as the major component on the basis of relative atomic percent. When expressed as $Fe_iIr_jGa_kSi_l$, wherein i, j, k, and l denote relative concentration in atomic percent, it is contemplated that FeIrGaSi, in accordance with the invention, should satisfy the following relationships:

1) $72.0 \leqq i \leqq 78.0$
2) $1.0 \leqq j \leqq 4.0$
3) $5.0 \leqq k \leqq 8.0$
4) $14.0 \leqq l \leqq 18.0$
5) $i + j + k + l = 100$

The invention has been described in detail with reference to the figures; however, it will be appreciated that variations and modifications are possible within the spirit and scope of the invention.

Claims

1. A thin film material, having a uniaxial magnetic anisotropic characteristic, comprised of FeIrGaSi.

2. An FeIrGaSi soft magnetic thin film having a uniaxial magnetic anisotropic characteristic of several Oersteds induced by magnetic annealing of sputtered FeIrGaSi in thin film form.

3. A magnetic material comprised of FeIrGaSi characterized by the property of uniaxial anisotropy and improved high-frequency permeability and wear resistance brought about by magnetic annealing of sputtered FeIrGaSi in thin film form at temperatures between 350 and 600°C.

4. An FeGaSi-based magnetic film containing Ir at a concentration of 1.0 to 4.0 atomic percent to improve the high-frequency soft magnetic property of said magnetic film.

5. An Fe-dominated FeGaSi-based magnetic film in which Fe is principally replaced by adding Ir at a concentration level of 1.0 to 4.0 atomic percent to improve the high-frequency soft magnetic property of said magnetic film.

6. An FeGaSi-based magnetic film containing Ir at a concentration of less than about 4.0 atomic percent to generally increase the Curie temperature of said magnetic film.

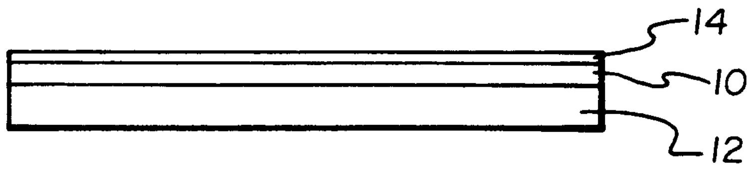
14
10
12

FIG. 1

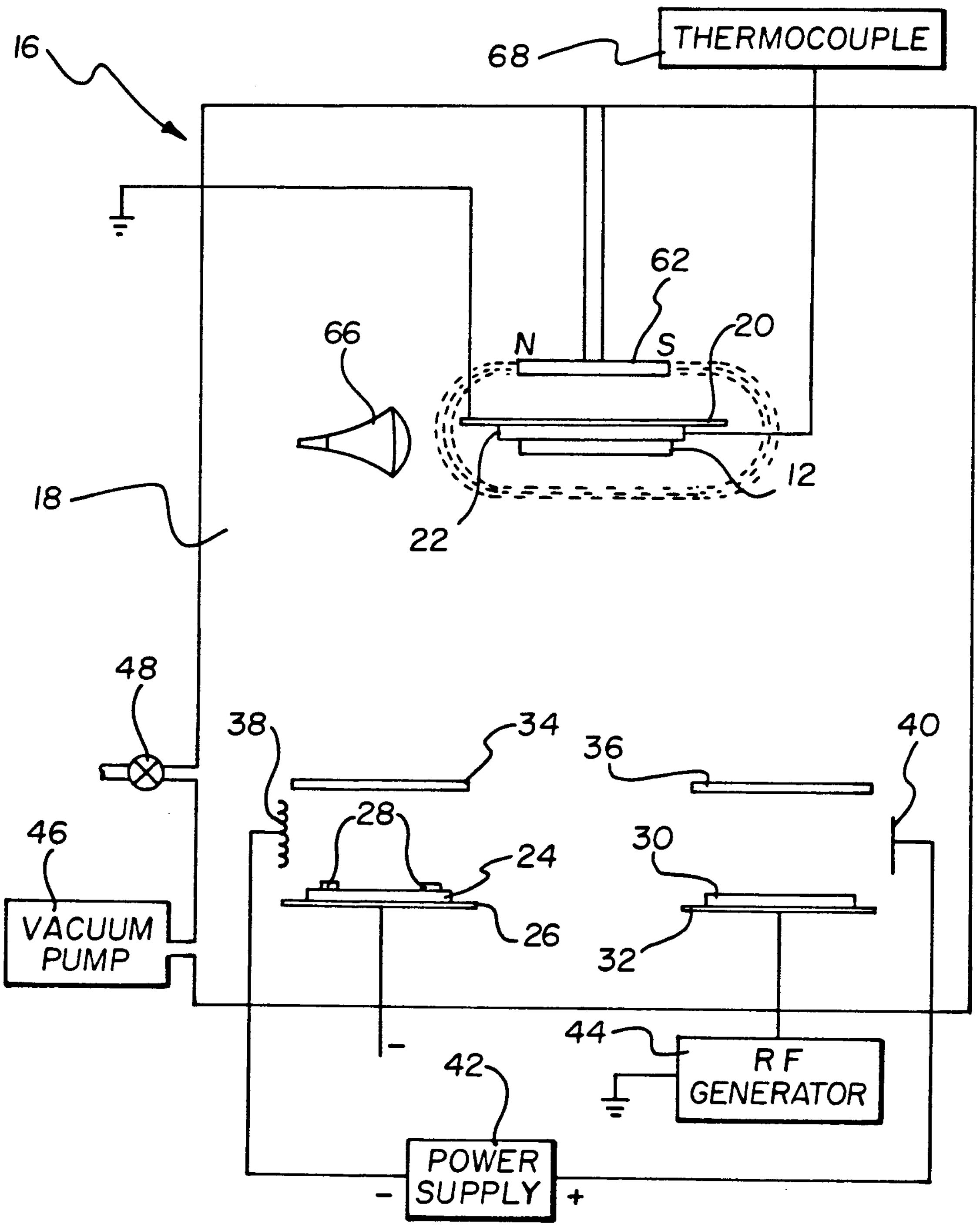
THERMOCOUPLE
68
16
62
66
N
S
20
12
18
22
48
38
34
36
40
28
46
24
30
VACUUM
PUMP
26
32
44
-
42
R F
GENERATOR
POWER
SUPPLY
-
+

FIG. 2

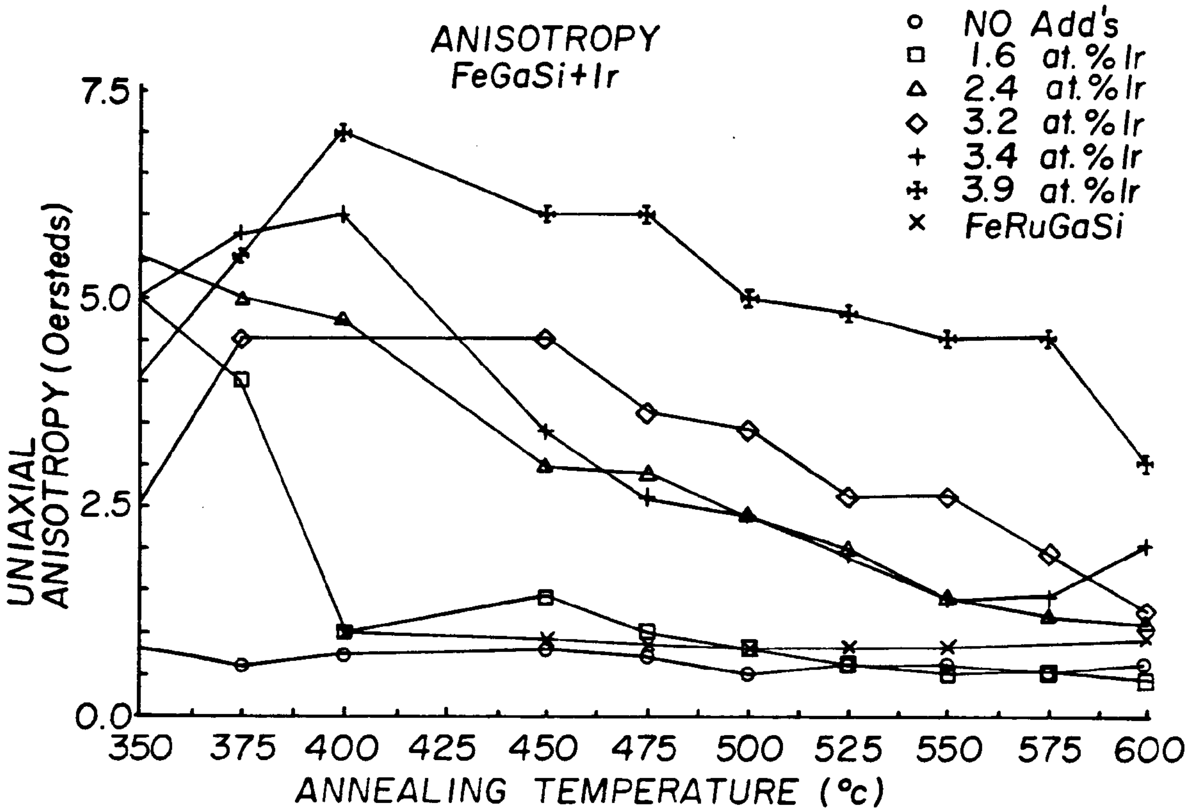
ANISOTROPY
FeGaSi+Ir
NO Add's
1.6 at.%Ir
2.4 at.%Ir
3.2 at.%Ir
3.4 at.%Ir
3.9 at.%Ir
FeRuGaSi
UNIAXIAL ANISOTROPY (Oersteds)
7.5
5.0
2.5
0.0
350
375
400
425
450
475
500
525
550
575
600
ANNEALING TEMPERATURE (°c)

FIG. 3

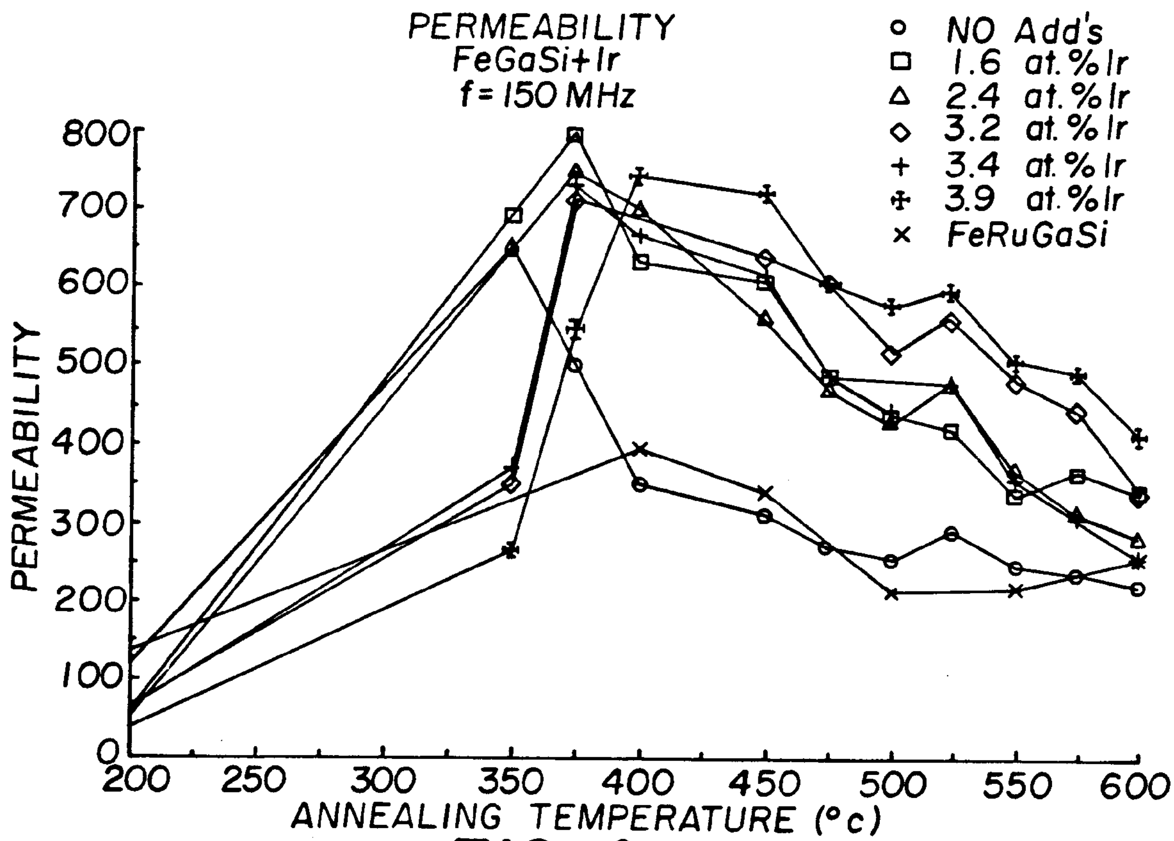
PERMEABILITY
FeGaSi+Ir
f=150 MHz
NO Add's
1.6 at.%Ir
2.4 at.%Ir
3.2 at.%Ir
3.4 at.%Ir
3.9 at.%Ir
FeRuGaSi
PERMEABILITY
800
700
600
500
400
300
200
100
0
200
250
300
350
400
450
500
550
600
ANNEALING TEMPERATURE (°c)

FIG. 4

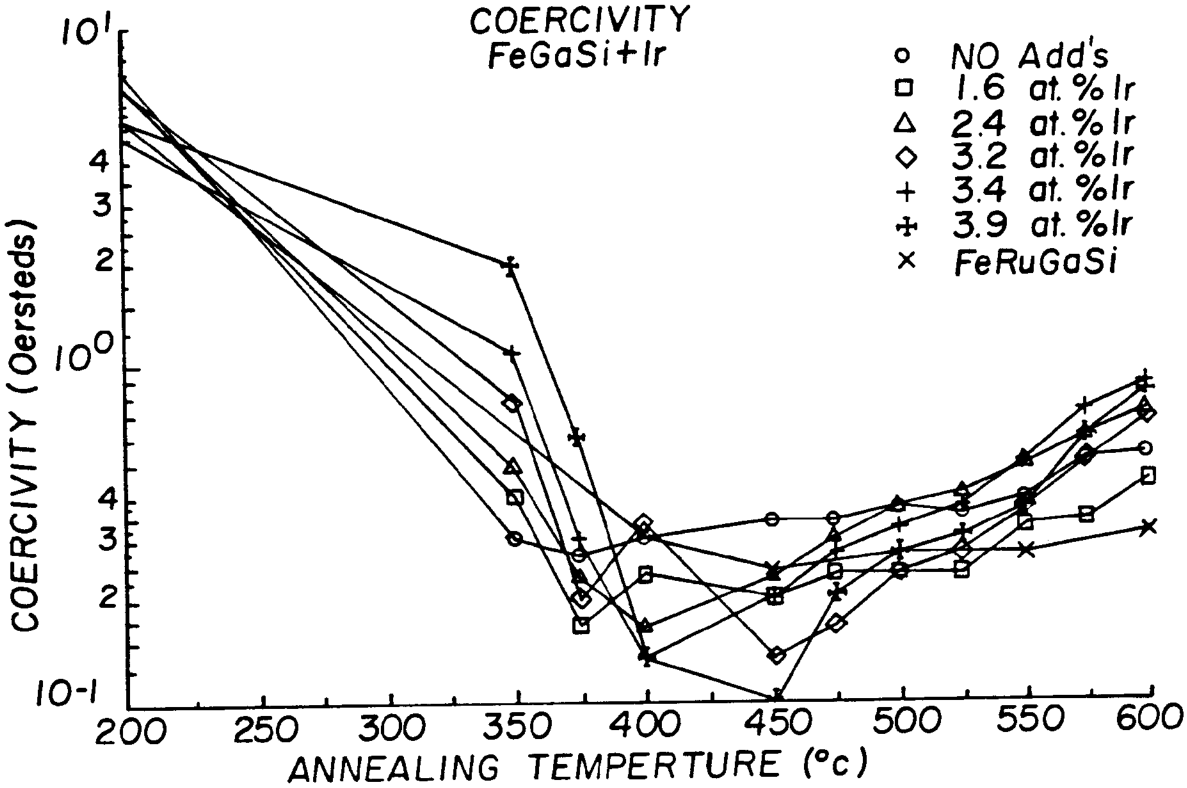

FIG. 5

COMPOSITION (at.%) AND
CURIE TEMPERATURE OF FeXGaSi (X=Ir or Ru)

SAMPLE	Fe	X	Ga	Si	Tc,C
FeGaSi	78.7	0.0	6.3	15.0	558
FeIrGaSi	77.3	1.6	6.4	14.7	563
FeIrGaSi	76.7	2.4	6.5	14.4	567
FeIrGaSi	76.4	3.2	6.2	14.2	572
FeIrGaSi	75.9	3.4	6.5	14.2	568
FeRuGaSi	72.3	7.3	5.8	14.5	545
FeRuGaSi	69.3	7.9	6.8	15.9	480
FeGaSi (target)	74.0	0.0	8.5	17.5	–

FIG. 6