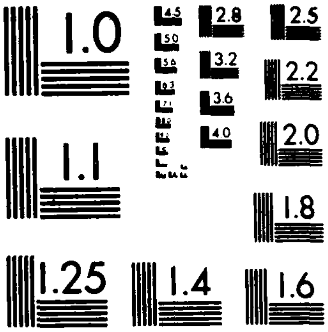
AD-A191 015 EPITAXIAL IRON FILMS(U) MINNESOTA UNIV MINNEAPOLIS 1/1
E D DAHLBERG ET AL. 31 JAN 88 AFOSR-TR-88-0043
AFOSR-86-0201

UNCLASSIFIED F/G 9/1 NL



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

FILE COPY ②

AD-A191 815

ORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION
UNCLASSIFIED

1b. RESTRICTIVE MARKINGS

2a. SECURITY CLASSIFICATION AUTHORITY

3. DISTRIBUTION/AVAILABILITY OF REPORT
Approved for public release,
distribution unlimited

2b. DECLASSIFICATION/DOWNGRADING SCHEDULE

4. PERFORMING ORGANIZATION REPORT NUMBER(S)

5. MONITORING ORGANIZATION REPORT NUMBER(S)
AFOSR-TR- 88-0043

6a. NAME OF PERFORMING ORGANIZATION
University of Minnesota

6b. OFFICE SYMBOL (If applicable)

7a. NAME OF MONITORING ORGANIZATION
Same as 8a

DTIC
ELECTE
FEB 24 1988
S D
E

6c. ADDRESS (City, State and ZIP Code)
Physics - 116 Church St. S.E.
Minneapolis, MN 55455

7b. ADDRESS (City, State and ZIP Code)
Same as 8b

8a. NAME OF FUNDING/SPONSORING ORGANIZATION
AFOSR/NE

8b. OFFICE SYMBOL (If applicable)
NE

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
AFOSR-86-0201

8c. ADDRESS (City, State and ZIP Code)
Bolling AFB
Washington, D.C. 20332-6448

10. SOURCE OF FUNDING NOS.

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT NO.
61102F	2306	C3	

11. TITLE (Include Security Classification)
Epitaxial Iron Films

12. PERSONAL AUTHOR(S)
E.D. Dahlberg -P.I. Cohen

13a. TYPE OF REPORT
Annual Report

13b. TIME COVERED
FROM 06/15/86 TO 12/14/87

14. DATE OF REPORT (Yr., Mo., Day)
31 Jan 1988

15. PAGE COUNT
12

16. SUPPLEMENTARY NOTATION

17. COSATI CODES

FIELD	GROUP	SUB. GR.

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)

19. ABSTRACT (Continue on reverse if necessary and identify by block number) Gallium Arsenide/Indium Arsenide

The growth properties and magnetic properties of iron films grown by molecular beam epitaxy were studied. The iron film growth was first studied by growing iron on iron whiskers. This work and previous work determined the growth parameters for nearly dislocation free growth. This information was then used to grow iron films on GaAs/InAs alloy substrates. As determined by electron diffraction, layer by layer growth was observed when the iron films were grown. The magnetic properties of the iron films were found to be dependent up on the substrate surface morphology and lattice constant. In particular the coercivity of epitaxed iron films was found to vary by roughly a factor of four when grown on different surface morphologies and substrate lattice spacings. Other research focused on the magnetotransport and magnetooptic properties of the iron films and the effects of the substrate lattice properties on them.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT
UNCLASSIFIED/UNLIMITED ☑ SAME AS RPT. ☐ DTIC USERS ☐

21. ABSTRACT SECURITY CLASSIFICATION
UNCLASSIFIED

22a. NAME OF RESPONSIBLE INDIVIDUAL
Dr. Weinstock

22b. TELEPHONE NUMBER (Include Area Code)
(202) 767-4933

22c. OFFICE SYMBOL
NE

DD FORM 1473, 83 APR EDITION OF 1 JAN 73 IS OBSOLETE.

SECURITY CLASSIFICATION OF THIS PAGE

DTIC
COPY
INSPECTED

ANNUAL REPORT FOR
AFOSR GRANT NO. AFOSR-86-0201

SUBMITTED TO
AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
BOLLING AFB, DC 20332-6448

Accession For	
NTIS GRA&I	☒
DTIC TAB	☐
Unannounced	☐
Justification	
By	
Distribution/	
Availability Codes	
Dist	Avail and/or Special
A-1	

Grant Title: Epitaxial Iron Films

Starting Date: 15 June 1986

Report Date: 31 January, 1988

Institution Name: University of Minnesota
Minneapolis, MN 55455

Co-Principal Investigators: E.D. Dahlberg, School of Physics & Astronomy, (612) 624-3506; P.I. Cohen, Dept. of Electrical Engineering, (612) 625-5517

Business Office: Merlin Garlid
Asst. Director and Grant Administrator
Office of Research & Technology Transfer Administration
1919 University Avenue
St. Paul, MN 55104
(612) 624-2088

Co-Principal Investigator
E. D. Dahlberg
Assistant Professor
(612) 624-3506

P I Cohen by
Co-Principal Investigator
P. I. Cohen
Associate Professor
(612) 625-5517

88 2 24 112

AFOSR-TR- 88-0043

I. Statement of Work

The research program is focused on the growth and characterization of epitaxial iron films grown on GaAs/InAs alloy substrates. The importance of growing the iron on the semiconductor alloys stems from the potential tuning of the magnetic properties of thin film magnets by varying the lattice constant and the morphology of the growth surface. This ability to tune the magnetic properties of materials and this type of research in general has both device and fundamental research applications. As an example of how one may modify the iron films one may consider that when grown on GaAs the Fe lattice is compressed from its equilibrium value by roughly 1.5%. With 100% InAs substrates, the Fe lattice would be expanded by roughly 7% (that an iron film would grow with this magnitude strain is unlikely however smaller values are not unreasonable). In general, the lattice constant of InGaAs alloys depends upon the mole fraction of In to Ga. Therefore by altering the mole fraction of In in a buffer layer, the magnetic properties of pseudomorphic Fe films can be modified and studied as a function of the Fe lattice constant. Our initial studies of Fe films grown on GaAs have revealed a number of interesting phenomena including a dynamic Fe-FeO coupling, and a correlation between lattice constant and surface morphology and the coercivity of the films. These studies, although interesting in their own right, have only scratched the surface of the potential of this research area. Our continued efforts in this area will systematically study the effect of the lattice constant and surface morphology on the magnetic properties of thin films.

In the growth studies reflection high energy electron diffraction determines the quality of the material and the growth mechanisms of the metal films. This part of the research provides information related to epitaxial processes in general and also provides the information to insure high quality surfaces and interfaces of the materials.

The magnetic studies rely on the transport properties of the films and magnetization measurements using both a superconducting susceptometer and a magnetooptic magnetometer. The transport measurements include the anisotropic magnetoresistance, the anomalous and regular Hall voltage and the planar Hall effect. The magnetization, coercivity energies, transport properties and magnetooptic properties of the films are studied as a function of film thickness, lattice constant and crystallographic orientation. The magnetic studies are and will be used for both a microscopic understanding of the effect of the lattice constant or strain on the magnetic properties of the films and also as exploratory studies for potential device applications based on epitaxial magnetic films.

II. Magnetic Properties of Epitaxial Iron Films

The initial research on the magnetic properties of the epitaxial magnetic films focused on the transport properties of films grown on the (110) surface of GaAs substrates (the films were prepared by the group of Dr. G. Prinz at the Naval Research Laboratory in Washington D.C.). A study of the transport properties and the more traditional magnetic properties of films grown on (100) GaAs are in progress (these latter films were grown by Prof. Cohen's group). We will first discuss the results of the transport studies of the (110) films and then the other studies of the (100) films by listing and discussing the publications which are either accepted for publication or are planned and last the areas of current research investigations.

A. "Saturation Magnetization and Perpendicular Anisotropy of Fe/GaAs (110) Epitaxial Films Studied by the Extraordinary Hall Effect," K.T. Riggs, E. Dan Dahlberg, and G. Prinz, accepted for publication in the Jour. of Magn, and Magn. Mat.

This paper involves measuring the extraordinary Hall effect (EHE) in (110) iron films. The study utilized eight films of varying thickness (from 5 to 20 nm). The study of the EHE provides a measure of the sum of the magnetization of the films and the surface anistropy energy. This study provides two important results for the understanding of the magnetic properties of epitaxial iron films. The first is that for films grown on the (110) surface of GaAs the magnitude of the surface anisotropy energy is not inordinately large. This result indicates the importance of the growth symmetry in epitaxial magnetic films since in (100) grown films the magnitude of this energy is sufficient to rotate the magnetization out of the plane of the film. The second important result included in this work is the variation of the results between transport measurements and ferromagnetic resonance which measures the same quantity. We have postulated that on the thinnest films the resonance measurement is observing a dynamic coupling of the metallic iron and the oxide on the surface whereas the transport is only sensitive to the metallic form. The implications of this result are that multilayered magnetic systems or magnetic systems where interfacial phenomena are important may have unique frequency dependent properties which could aid certain technologies.

B. "Magnetotransport: An Ideal Probe of Anisotropy Energies in Epitaxial Films," E. Dan Dahlberg and K.T. Riggs, Invited paper to the 1987 Magnetism and Magnetic Materials Conference accepted for publication in the J. of Appl. Phys.

This invited paper stems from our use of transport to determine the magnetic properties of epitaxial magnetic films. In general the transport measurements provide an ideal tool to study the magnetic properties of epitaxial magnetic films. More traditional techniques such as SQUID magnetometry require the subtraction of any magnetic contribution of the substrate materials and although the substrate magnetism is small per unit of volume or mass, because the amount of substrate present is large it typically creates a difficult subtraction problem. The transport, on the other hand, measures only the metallic portion of the substrate/film combination and therefore for epitaxed metals on semiconductor/insulator substrates frees one of the usual subtraction problems.

C. "Magnetic Properties of MBE Grown (100) Iron Films," D.K. Lottis, E. Dan Dahlberg, S. Batra, A.M. Wowchak, and P.I. Cohen, accepted for publication in the J. of Appl. Phys. (presented at the 1987 Magnetism and Magnetic Materials Conference).

We have observed that the magnetic properties of (100) epitaxial iron films are dependent upon the surface preparation of the substrate. The iron films studied in this publication were grown on smoothed GaAs (epitaxed GaAs surface layer), chemically polished GaAs, and lattice matched InGaAs substrates. The measured coercivities were found to vary by a factor of four for the various substrates with the smooth GaAs sample having the smallest value. Although we do not presently have a detailed model to explain the origin of the effect it appears that both the lattice match and the smoothness of the substrate are very important in controlling the coercivity. By understanding exactly what the effects are and how they are controlled would allow us to grow iron films with prespecified coercivities for specific applications.

D. "Study of a Magnetic Field Induced First Order Phase Transition," K.T. Riggs, E. Dan Dahlberg, and G. Prinz, to be submitted to either J. of Appl. Phys. Lett. or Phys. Rev. Rapid Comm.

This manuscript has been outlined and the analysis of the necessary data has been completed. It is anticipated that the manuscript will be submitted for publication by July, 1988. It had been anticipated that the manuscript would be complete by this time however the graduate student working on this project has accepted a Professorship at Stetson College in Florida which has slowed the progress on the completion of this paper. He will return in the summer of 1988 to finish his PhD.

This study focuses on the rotation of the saturation magnetization in the plane of the epitaxial iron films and utilizes the anisotropic magnetoresistance to follow the rotation of the magnetization in the presence of magnetic fields applied parallel to the plane of the films. As mentioned in A. above, the surface anisotropy energy in the (110) films is insufficient to rotate the magnetization out of the plane of the films. With the magnetization pinned in the plane of the film then the rotation of the magnetization in the plane of the films as a function of the magnitude and direction of a magnetic field applied in the plane of the film can be modeled as a first order transition. The easy way to understand this behavior is to consider two easy axes separated by a hard axis in the plane of the film. If the magnetization is required to rotate from one easy axis to the other by the application of a magnetic field, the applied magnetic field must be of sufficient strength that the magnetization can pass by the hard axis. Once this occurs the magnetization then abruptly (in a first order sense) makes the transition to the other easy axis. In the analysis of this behavior the uniaxial and fourth order anisotropy energies of the epitaxial films can be determined.

E. "A Study of the Transport Properties of Epitaxial Iron Films," K.T. Riggs, E. Dan Dahlberg, and G. Prinz, to be submitted to Phys. Rev.

This work will include all of the transport results not reported in the two previous publications and will discuss the relation of the magnetic properties as determined by the various transport studies. This manuscript will be a major portion of the dissertation of K.T. Riggs and will not be submitted for publication until August, 1988. Some of the transport measurements not reported elsewhere which will be presented in this paper are the ordinary Hall effect results and the magnitude of the spin-orbit coupling as determined by the anisotropic magnetoresistance.

F. Other research areas: The spin-orbit interaction studied by the temperature dependence of the anisotropic magnetoresistance magnetooptic properties, and anisotropy energies, interfacial effects on coercivities, and free surface oxide stability.

It is anticipated that the largest effect of an altered iron lattice constant will be in those properties which depend up on the spin-orbit coupling. This has been shown already in iron films grown on GaAs substrates which compresses the iron lattice. This compression alters the spin-orbit coupling which determines the anisotropy energies in magnetic systems. In these films the small alteration of the lattice constant is sufficient to rotate the easy axis from the (100) direction to the (110) direction. The spin-orbit coupling is the fundamental mechanism which determines the anisotropic magnetoresistance, the magnetoelastic coupling, the magnetooptic coupling, and provides a fundamental limit for the coercivity via the anisotropy energies. Although this one interaction is of fundamental and technical importance it is still not well understood theoretically. For this reason we are systematically studying many of the material properties which depend upon the spin-orbit coupling in order to provide the necessary information to develop a basic understanding and model of this interaction.

As we briefly discussed in section C. above, we have found large variations in the coercivities of the films prepared at Minnesota. Although there are phenomenological models of how defects and strains alter coercivity there as yet has not been definitive testing of these models. In part the reason for this is samples have not been characteized well enough to know of of the defects and impurities present. For the iron samples we have prepared by MBE, the morphology of the substrate and the iron films are characterized by electron diffraction from the surfaces and the chemical composition is monitored by Auger electron spectroscopy. These tools used as a quantification of the disorder present should be sufficient to test some of the models for the coercivity.

The last area of research we will discuss is the determination of the oxide which forms on the iron surface when removed from the MBE system. In general iron does not form a passivating oxide surface. The reason is that the normal oxides of iron such as FeO_2 and Fe_2O_3 do not match the iron lattice which causes a strain at the iron/iron oxide interface. This strain increases until the oxide fractures exposing fresh iron which in turn oxidizes. This process continues until the iron has been completely oxidized. In the case of the iron films we have been studying, some of them were made as long ago as 1985. These films of which the thinnest is 7.5 nM, are still metallic, i.e., they are not completely oxidized. This remarkable result is most likely due to the lack of grain boundarys and the formation of an unusual oxide such as FeO. In the next few months we will perform EXAFS using the facilities in the surface science center at Minnesota to determine the valence of the iron and oxygen on the surface of the films.

III. Growth of Epitaxial Iron Films.

Molecular beam epitaxy has been used to prepare clean, ultra-thin epitaxial iron films on Fe(001), GaAs(001) and InGaAs(001). By preparing smooth, dislocation free surfaces of GaAs and InGaAs the role of the Fe-InGaAs interface in the growth and magnetic properties of ultrathin Fe Films can be examined. The growth and smoothness of the surface was determined in-situ using reflection high-energy electron diffraction (RHEED).

A. Iron source - design and calibration

An iron source has been developed that provides a clean stable iron flux. This source is composed of a 0.020" iron wire wrapped around a .030" tungsten wire. Direct current heating of the tungsten to a constant temperature causes the iron wire to sublimate at a given rate. The sublimation rate used is calibrated at about 1-2 angstroms/minute at the sample surface as determined using RHEED oscillations on a iron whisker. This is discussed further below.

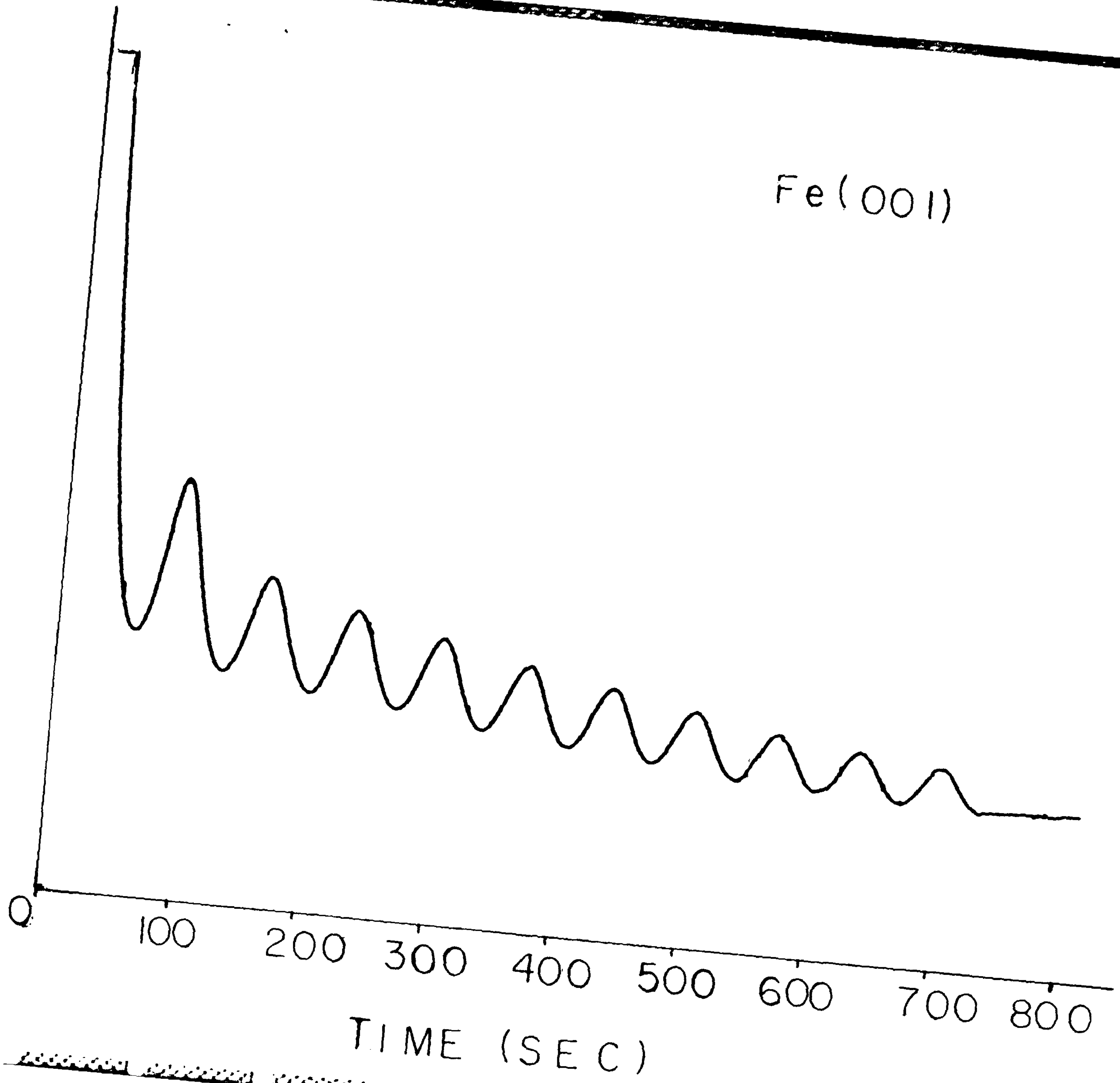
B. Growth of iron on iron whiskers

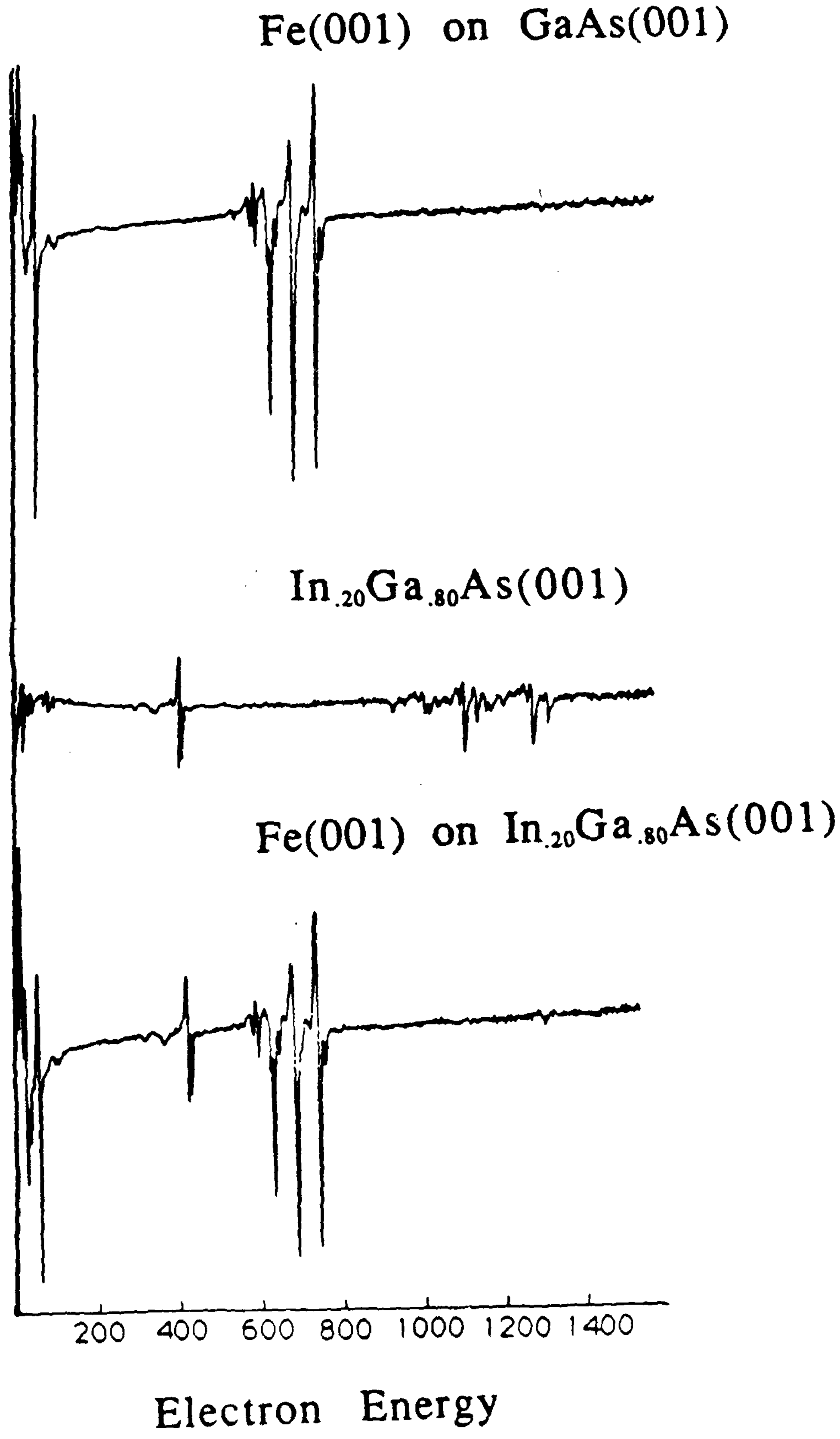
Iron was grown on iron whiskers to better understand the growth properties of iron and to calibrate the iron source. The whisker was prepared by sputtering at 700°C with 2 keV argon ions and then annealing at the same temperature. Auger spectroscopy of the surface prepared in the above manner showed surface contamination of less than 5% carbon and oxygen. Two dimensional growth as indicated by RHEED intensity oscillations was found to occur in the temperature range of 150-300°C (Figure 1). These oscillations, which correspond to the growth of a monolayer of material, served as a method to calibrate the iron source flux at the sample position.

C. Growth of iron on GaAs(001)

Epitaxial iron films approximately 100 Angstroms thick were grown on smooth, clean, extremely flat MBE grown GaAs(001) surfaces at 65°C. These films showed good epitaxial growth on the surface but in striking contrast to Fe on Fe(001) layer by layer growth has not yet been achieved. Instead, the RHEED patterns show iron clusters forming three dimensional islands on the surface. In the future the substrate will be cooled below room temperature to reduce the iron mobility and consequently form flatter surfaces and achieve layer by layer growth. Auger spectroscopy (AES) of the iron film shows a very clean iron surface with only a slight hint of arsenic (Figure 2a).

When the iron films are annealed to approximately 400°C the iron forms large amorphous clusters exposing the underlying GaAs surface as shown by RHEED and AES. This demonstrates that iron has a much stronger affinity for itself than the underlying substrate. A study is underway to determine the influence of the GaAs(001) surface reconstruction (Ga rich or As rich) on the growth and magnetic properties of the iron film. This will determine whether one can control the diffusion of Fe in GaAs by changing the surface structure.


Fe(001)
0
100
200
300
400
500
600
700
800
TIME (SEC)


Fe(001) on GaAs(001)
$In_{.20}Ga_{.80}As(001)$
Fe(001) on $In_{.20}Ga_{.80}As(001)$
200
400
600
800
1000
1200
1400
Electron Energy

D. Growth of iron on InGaAs(001)

Iron films approximately 100 Angstroms thick were grown on lattice matched InGaAs and slightly mismatched InGaAs surfaces at 175°C. The InGaAs(001) substrates were not as flat as the GaAs surfaces due to dislocations formed during growth. Strained layer superlattice buffers that would turn the dislocations back into the bulk of the buffer will be attempted in the future. The iron films grown on this surface again show epitaxial growth and seem as smooth as those grown on the GaAs surface. Here, as with GaAs, the surface must be cooled to achieve layer by layer growth. Also, Indium was observed to segregate to the Fe surface (Figure 2c). In the future a pseudomorphic diffusion barrier grown on InGaAs will be tried.

IV. Personnel

A. Batra,S., Post-doctoral appointment has now left the group and is presently employed by Digital Equipment Co.

B. Jamison,K.D., Post-doctoral appointment

C. Kuznia J.N., Graduate Student in Electrical Engineering

D. Wowchak,A.M., Graduate Student in Electrical Engineering

E. Riggs,K.T., Graduate Student in Physics (PhD to be received in 1988 presently an Assistant Professor at Stetson College in Florida)

F. Lottis,D.K., Graduate Student in Physics

G. Florczak,J.T., Graduate Student in Physics

END
DATE
FILMED
5-88
DTIC