LBL-22376
Preprint

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Materials & Chemical Sciences Division

RECEIVED
LIBRARY
JAN 22 1987
DOCUMENTS SECTION

Center for Advanced Materials

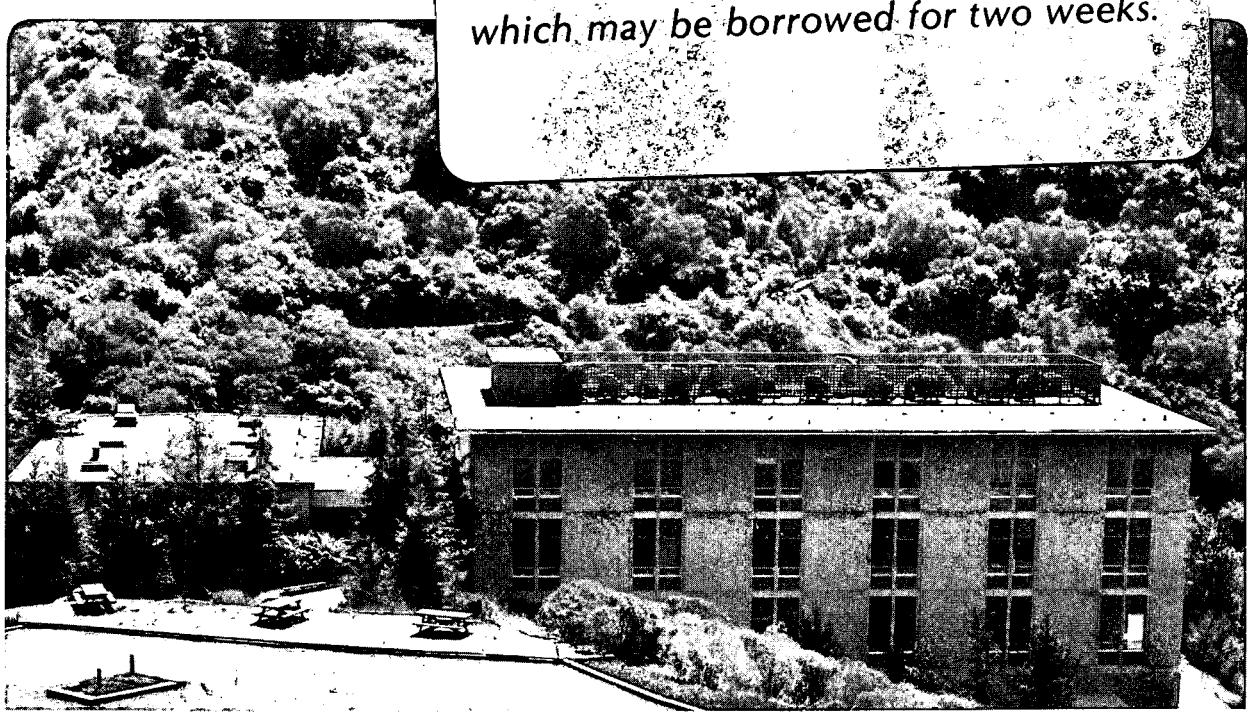
Submitted to Journal of Applied Physics

INTERFACIAL INTERACTIONS OF EVAPORATED IRIDIUM THIN FILMS WITH (100) GaAs

K.M. Yu, T. Sands, J.M. Jaklevic, and E.E. Haller

January 1987

TWO-WEEK LOAN COPY
This is a Library Circulating Copy which may be borrowed for two weeks.



LBL-22376 c.2

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

INTERFACIAL INTERACTIONS OF EVAPORATED IRIDIUM THIN FILMS WITH (100) GaAs

Kin Man Yu, T. Sands[a], J. M. Jaklevic and E. E. Haller

Center for Advanced Materials and Engineering Division, Lawrence Berkeley Laboratory and University of California, Berkeley, Ca 94720.

We present the first report on a systematic study on thermally activated solid phase reactions between (100) GaAs and evaporated iridium thin films (100 Å and 550 Å thick). The investigation is carried out with Rutherford backscattering spectrometry, x-ray diffraction and transmission electron microscopy. Interfacial interactions are observed after annealing the system at temperatures higher than 500°C. Complete reaction at 700°C results in the formation of Ir_3Ga_5 and $IrAs_2$ phases. Intermediate phase IrGa is formed in the annealing temperature range of 500-650°C. Vertical phase segregation is also observed with the $IrAs_2$ phase at the interface and the Ir-Ga phases on the surface layer.

Specific information on the reaction kinetics, transformation and structures of different phases and phase distributions are also discussed. Comparisons with interfacial reactions of other near noble metal/GaAs systems are presented. Based on the metallurgical information obtained, the potential applications of this contact system are suggested.

[a]Bell Communications Research, Inc., 331 Newman Springs Rd., Red Bank, NJ07701.

I. INTRODUCTION

In recent years, metal/III-V compound semiconductor interfaces, in particular metal/GaAs interfaces, have attracted much attention because of the contact problems encountered in the developments of III-V integrated circuits. Since electrical properties of metal/GaAs contacts are sensitive to interface reactions, a great deal of work has been devoted to the studies of the metallurgy at the interfaces of metal/GaAs contacts. Thin films of group VIII near noble metal (for example, Co, Pd, Ir, Ni, Rh and Pt)/GaAs contacts are of particular interest because of their reactive nature. Since near noble metals react with both group III (Ga) and group V (As) atoms at low temperatures (~200-500°C) [1-14], there is no depletion or accumulation of the anion or cation beneath the reacted layer. Therefore the stoichiometry of III-V (GaAs) substrate at the interface is preserved. Interface states due to point defects or defect complexes created by non-stoichiometry are thus minimized.

Another attractive property of near noble metals is that they are highly resistive to oxidation (especially Pd, Pt and Ir). Moreover, near noble metals have also been known to form high Schottky barrier heights with n-GaAs (~0.75 to 0.9 eV) [15]. This makes them attractive candidates as contact materials for high barrier GaAs Schottky diodes and tunneling ohmic contacts. In fact, nearly all reported GaAs "sintered" ohmic contact involved one of the near noble metals, Ni [16,17], Pd [18,19] and Pt [20]. The roles these near noble metals play in these "sintered" ohmic contacts are, however, still unknown.

In order to exploit the potential of the near noble metal films as contact materials to GaAs (and III-V semiconductors in general) the metallurgy at the simple near noble metal/GaAs interfaces must be thoroughly understood. In

this paper we present the first systematic study of the solid phase reactions between (100) GaAs and thin films of one of the near noble metal, iridium. Rutherford backscattering spectrometry (RBS), x-ray diffraction (XRD) and transmission electron microscopy (TEM) measurements are performed on 100 Å and 550 Å thick iridium films deposited on (100) GaAs substrates. Reaction kinetics as well as formation sequence, structures, morphology and distributions of different phases are investigated.

II. EXPERIMENTAL

Undoped semi-insulating ($\rho > 10^7 \Omega$-cm) GaAs substrates in (100) orientation (Wacker Chemitronic [21]) were degreased in organic solvents followed by etching in a 50% HCl solution for one minute in order to remove the native oxide on the GaAs surface. The wafers were rinsed in deionized water and blown dry with N_2. Iridium films 100 Å and 550 Å thick were deposited on the two wafers by electron gun evaporation at a pressure below 10^{-6} torr. The metallized wafers were then cut into small pieces (~ 4mmX 4mm) and capped on both sides with ~ 2000 Å of SiO_2 in order to minimize the sublimation of As during annealing. The SiO_2 films were deposited by plasma enhanced chemical vapor deposition at a substrate temperature below 200°C. The samples were then annealed in flowing N_2 ambient at temperatures ranging from 300 to 700°C for various time durations. Finally the oxide caps were removed from the annealed samples by dipping the samples in a buffered HF solution for 2 minutes.

Rutherford backscattering spectrometry measurements were performed with a 2.0 MeV $^4He^+$ beam generated by a 2.5 MeV Van de Graaff accelerator. The ion beam was collimated down to 1 mm in diameter on target. Energy resolution

of ~18 keV (FWHM) was obtained with a silicon surface barrier detector located at a backscatter angle of 165°. Samples with 100 Å Ir films were tilted at 65° with respect to the beam so that depth an improved resolution δx~ 20 Å (FWHM) could be achieved. Normal incident RBS measurements were performed on samples with 550 Å Ir films (δx~ 100 Å).

Samples with ~100 Å Ir films were further characterized by plan-view transmission electron microscopy. TEM measurements were carried out with a Siemans 102 TEM at 100 keV. X-ray diffractions in the Bragg-Brentano geometry were performed on samples with 550 Å Ir films. The combination of electron diffraction and XRD data facilitate conclusive phase identification.

III. RESULTS AND DISCUSSIONS

A. 550 Å Ir Film

A two stage reaction is detected with RBS in the 550 Å Ir/GaAs system. Initial interfacial interaction starts during annealing at 500°C. Complete consumption of the entire Ir film is observed in the sample annealed at 650°C for 80 min (stage 1). The final reaction is completed after annealing at 700°C for 16 min (stage 2). Figure 1 shows the RBS spectra from 550 Å Ir/GaAs samples as deposited, annealed at 650°C for 80 min and 700°C for 16 min. It can be oberved from the Ir signals in the spectra that two-layer structures are formed in both of the annealed samples. The interface layers in these two annealed cases have similar Ir concentration while the top layer in the sample annealed at 650°C has higher Ir content than that of the sample annealed at 700°C. The GaAs signals in the backscattering spectra show no significant amount of As present in the top layers in both annealed samples.

Deconvolutions of the RBS spectra from the two annealed samples are shown in figure 2. Well defined layered structures with Ir-As phase at the interface and Ir-Ga phase on top are evident. Height ratio analysis of the RBS spectra gives [Ir]:[Ga] ≈ 1:1 and [Ir]:[As] ≈ 1:2 for the sample annealed at 650°C for 80 min and [Ir]:[Ga] ≈ 0.6:1 and [Ir]:[As] ≈ 1:2 for the sample annealed at 700°C for 16 min. Overall ratios of the reacted Ir and GaAs are also obtained from energy loss analysis of the two RBS spectra in figure 2 and yields [Ir]:[GaAs] ≈ 1.5:1 for stage 1 reaction and ≈ 1.1:1 for stage 2 reaction. These data are consistent with the following reactions:

$3\ Ir + 2\ GaAs \rightarrow 2\ IrGa + IrAs_2$ (stage 1), and

$11\ Ir + 10\ GaAs \rightarrow 2\ Ir_3Ga_5 + 5\ IrAs_2$ (stage 2).

Table I gives a summary of the RBS results on the 550 Å Ir/GaAs system.

XRD measurements on 550 Å Ir/GaAs samples annealed at temperatures ranging from 500 to 650°C indicate the existence of two phases: cubic IrGa (a_0=3.004 Å) with CsCl structure and monoclinic $IrAs_2$ (a_0=6.060 Å, b_0=6.071 Å, c_0=6.158 Å and β=113°16'). Figure 3 (a) and (b) show two XRD spectra from samples annealed at 650°C for 20 and 80 min. Note that the IrGa and $IrAs_2$ diffraction peaks grow at the expense of the Ir peaks. After annealing at 700°C for 16 min the IrGa diffraction peaks disappear in the XRD spectrum as shown in figure 3 (c). A new set of diffraction peaks is detected in this spectrum. This set of diffraction data is in reasonable agreement with those of the tetragonal Ir_3Ga_5 phase [22] (a_0=5.823 Å and c_0=14.20 Å).

The RBS and XRD results suggest that the final stable phases for thin film Ir/GaAs solid phase reactions are the Ir_3Ga_5 and $IrAs_2$ phases. Intermediate phase IrGa decomposes at temperatures higher than 650°C. Moreover, vertical phase separation with a layer of $IrAs_2$ in intimate contact with GaAs and the Ir-Ga phase on top of the $IrAs_2$ layer is always observed in

this system. Similar phase stratification phenomena have also been oberved for other thin film near noble metal/GaAs systems such as the Pt [11-14, 23] and Rh [10,14]/GaAs systems. Sands et al. [14] studied this phenomenon for near noble metal/GaAs systems and concluded that phase stratification resulted when the grain size in the reacted film was smaller than the reacted film thickness. They also found that for metal/GaAs systems annealed under the same conditions, the grain size in the reacted film was larger for deposited metals with smaller heat of vaporization which could be related to the metal-metal bond strength. Since Ir has the highest heat of vaporization among the near noble metals, it has the smallest grains in the reacted layer. Owing to the relatively low mobility of the As in the reacted layer, the metal-As phase in those systems where phase stratification occurred always resided at the interface in intimate contact with the GaAs substrate.

Kinetics of the solid phase reactions between (100) GaAs substrate and Ir thin film is also studied with RBS by measuring the GaAs consumption at different annealing conditions. Plots of the square of the reacted GaAs thickness in molecules/cm^2 as a function of the annealing time for different annealing temperatures are shown in figure 4. All the plots in figure 4 show linear dependences indicating that the reactions at the Ir/GaAs interface follow parabolic rates and thus follow a diffusion controlled process. Diffusivity D at a certain annealing temperature T is a direct function of the diffusion coefficient at T and is deduced from the slope of the plot in figure 4 for T. An Arrhenius plot of ln D versus the reciprocal of the annealing temperature in degrees Kelvin is shown in figure 5. From figure 5, it can be seen that the Ir/GaAs reaction follows an exponential expression of the form $D \sim \exp[-\Delta E/kT]$ where ΔE is tne activation energy of reaction and k is the Boltzman constant. Activation energy of the reaction ΔE is thus obtained from

the slope of the plot and is 3.15±0.20 eV.

XRD spectra from the 550 Å Ir/GaAs samples annealed at 700°C for 9 min (not shown) and 16 min (figure 3(c)) reveal that unreacted Ir, IrGa and $IrAs_2$ are present in the former but Ir_3Ga_5 and $IrAs_2$ result in the latter sample. The fact that the formation of the Ir_3Ga_5 layer proceeds in such a rapid rate suggests that the process may be nucleation controlled. This has been observed in the formation of $NiSi_2$ [24], $IrSi_3$ [25], Rh_4Si_5, Rh_3Si_4 [26] and the rare earth metal silicides [27, 28]. This process happens at high temperatures (usually high than 700°C except for the rare earth silicides) when the diffusing atoms are so mobile that diffusion is very rapid. As a result the growth is no longer controlled by diffusion but is controlled by the nucleation process which happens at the interface with seemingly explosive suddenness.

The reaction kinetics data for Ir/GaAs are tabulated in Table II in comparison with those of other near noble metal/GaAs systems reported in the literature. The data in Table II show that the Ir/GaAs system has an activation energy of reaction twice as high as the other systems. Consequently relatively higher temperature is needed (≈ 500°C) to initiate reaction between Ir and GaAs. All the systems in Table II follow a parabolic reaction rate indicating that a diffusion limited process is the dominant process for the solid phase reactions of thin film near noble metal/GaAs contacts.

B. <u>100 Å Ir Film</u>

Figure 6 shows the diffraction pattern and the bright field image of the TEM measurement on 100 Å Ir/GaAs sample annealed at 600°C for 20 min. The presence of the Ir_3Ga_5 and $IrAs_2$ phases are revealed from the electron

diffraction pattern. Since thinner film promotes higher rate of reaction, it is not surprising to find the final stable phases at temperatures below 700°C. Very fine grains (~ 100 to 200 Å) are formed in the reacted layer as noticed in the TEM micrograph in figure 6. Strong texturing is observed in the diffraction pattern only for the $IrAs_2$ phase with the orientation relationship:

$$\langle 5\bar{2}1\rangle_{IrAs_2} // \langle 100\rangle_{GaAs}$$

$$\{11\bar{3}\}_{IrAs_2} // \{011\}_{GaAs}$$

The fact that the Ir_3Ga_5 phase bears no orientation relationship with the GaAs substrate suggests a layer sequence of $Ir_3Ga_5/IrAs_2/GaAs$ for this sample.

A glancing angle RBS spectrum from 100 Å Ir/GaAs sample annealed at 600°C for 20 min is shown in figure 7. Deconvolution of the spectrum (dashed spectrum) clearly confirms the layered structure as interpreted from the TEM results. Interpenetration of the two phases can also be deduced from the spectrum. Comparing with the thicker film case in which a distinct layered structure is always preserved, perfect distinction between the layers is lost in the very thin films because interface energy plays an important role. When the reacted film thickness becomes comparable to the grain size, phase stratification becomes thermodynamically less favorable. This effect has also been observed in the solid phase reactions in thin film Rh/GaAs [10,14] and Co/GaAs [14]. Since the reacted film in this system has a thickness of ~ 400 Å while the grain size of the reacted phase is ~ 150 Å in diameter, phase stratification results.

IV. CONCLUSIONS

From the results of the TEM, XRD and RBS measurements on 100 Å and 550 Å Ir/GaAs discussed above, the solid-state reactions between thin film Ir and (100) GaAs substrate can be summarized as follows:

1. The Ir/GaAs interface reacts in two stages. In the first stage, from 500°C to 650°C, IrGa and $IrAs_2$ phases are formed. The IrGa phase transforms into the more stable Ir_3Ga_5 phase in the presence of unreacted Ir in the second stage reaction at a temperature higher than 650°C. Therefore the Ir_3Ga_5 and $IrAs_2$ phases are the stable final phases for this system.
2. The Ir/GaAs reactions follows a parabolic reaction rate with a high activation energy ≈ 3.15 eV.
3. The reacted layer has very fine grains (~ 150 Å) so that phase stratification with the sequence Ir-Ga/Ir-As/GaAs is always observed.

Comparing with other near noble metal/GaAs systems, the Ir/GaAs contact system has the following unique characteristics:

1. It has the highest activation energy of reaction and therefore has relatively high thermal stability.
2. Due to the very fine grain size in the reacted layer, the Ir/GaAs system has a very sharp and distinct layered structure after reaction. Although the Pt and Rh/GaAs systems also exhibit phase stratification after reaction, because of their relatively larger grain sizes in the reated layers (~ 500 Å in diameter [12]) the interfaces between phases are less abrupt.
3. It has the lowest metal content in the final reacted layer. The ratios of the final reacted metal to GaAs in most near noble metal/GaAs sytems

have values less than or equal to 1.5. In the case of the Ir/GaAs system, this ratio is ≈ 1.1. This can be a disadvantage in the fabrication of shallow junction contacts in which little consumption of the substrate material is desirable.

4. Cubic MGa (M=Pt, Pd, Ni, Co and Rh) with CsCl structure is the most common stable phase formed for near noble metal/GaAs reactions . In the Ir/GaAs system, however, the cubic IrGa phase is unstable at high temperatures and transforms into the more stable Ga rich tetragonal Ir_3Ga_5 phase.

Instabilities in the electrical properties of a contact are always the result of either phase transformation or interdiffusions at the GaAs interface at elevated temperatures [10]. Since in the Ir/GaAs contact the stable $IrAs_2$ phase with an abrupt interface is always in intimate contact with the GaAs substrate at annealing temperatures higher than 500°C, it is expected that this system is electrically stable at high temperatures (up to ~700°C). This makes the Ir metal an attractive material for GaAs devices which require high temperature processing such as the self-aligned gate metal/GaAs field effect transistors. However, investigations on the electrical properties have to be carried out in order to complete the characterizations and exploit the applicabilities on this contact system.

ACKNOWLEGMENTS

The authors thank the technical assistance of W. L. Searles for the RBS facility at LBL and S. K. Cheung for SiO_2 capping.

This work was supported by the Director, Office of Basic Energy Research, Office of Basic Energy Sciences, Materials Science Division of the U. S. Department of Energy under Contract No. DE-AC03-76SF00098.

REFERENCES

1. A. J. Yu, G. J. Galvin, C. J. Palmstrom and J. W. Mayer, Appl. Phys. Lett. 47, 934 (1985).

2. T. S. Kuan, Mat. Res. Soc. Symp. Proc. 31, 143 (1984).

3. T. S. Kuan, J. L. Freeouf, P. E. Batson and E. L. Wilkie, J. Appl. Phys. 58, 1519 (1985).

4. T. Sands, V. G. Keramidas, R. Gronsky and J. Washburn, Mat. Lett 3, 409 (1985).

5. T. Sands, V. G. Keramidas, A. J. Yu, K. M. Yu, R. Gronsky and J. Washburn, Mat. Res. Soc. Sypm. Proc. 54, 367 (1986).

6. T. Sands, V. G. Keramidas, R. Gronsky and J. Washburn, Thin Solid Films 136, 105 (1986).

7. A. Lahav, M. Eisenberg and Y. Komen, Mat. Res. Soc. Symp. Proc. 37, 641 (1985).

8. A. Lahav, M. Eisenberg and Y. Komen, J. Appl. Phys. 60, 991 (1986).

9. T. Sands, V. G. Keramidas, J. Washburn and R. Gronsky, Appl. Phys. Lett. 48, 402 (1986).

10. K. M. Yu, S. K. Cheung, T. Sands, J. M. Jaklevic and E. E. Haller, to be published, J. Appl. Phys. (Manuscript No. LR8106, 1987).

11. V. Kumar, J. Phys. Chem. Solids 36, 535 (1975).

12. C. Fontaine, T. Okumura and K. N. Tu, J. Appl. Phys. 54, 1404 (1983).

13. T. Sands, V. G. Keramidas, A. J. Yu, K. M. Yu, R. Gronsky and J. Washburn, to be published, J. Mat. Res. (1986).

14. T. Sands, V. G. Keramidas, K. M. Yu, J. Washburn and K. Krishnan, to be published, J. Mat. Res (1987).

15. G. Y. Robinson, "Schottky Diodes and Ohmic Contacts for the III-V Semiconductors" in: Physics and Chemistry of III-V Semiconductor Interfaces, C. W. Wilmsen, ed. (New York, Plenum Press), 1985.

16. W. T. Anderson, Jr., A. Christou and J. E. Davey, J. Appl. Phys. 49, 2998 (1978).

17. S. R. Smith and J. S. Solomon, Mat. Lett. 3, 294 (1985).

18. H. R. Grinolds and G. Y. Robinson, Solid State Electron. 23, 973 (1980).

19. E. D. Marshall, W. X. Chen, C. S. Wu, S. S. Lau and T. F. Kuech, Appl. Phys. Lett. 47, 298 (1985).

20. K. Tsutsui and S. Furukawa, J. Appl. Phys. 56, 560 (1984).

21. Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U. S. Department of Energy to the exclusion of others that may be suitable.

22. JCPDS data file α19-490.

23. K. M. Yu, J. M. Jaklevic and E. E. Haller, Mat. Res. Soc. Symp. Proc. 69, 281 (1986).

24. F. M. d'Heurle and P. Gas, J. Mat. Res. 1, 208 (1986).

25 S. Petersson, J. Baglin, W. Hammer, F. d'Heurle, T. S. Kuan, I. Ohdomari, J. de Sousa Pires and P. Tove, J. Appl. Phys. 50, 3357 (1979).

26. S. Petersson, R. Anderson, J. Baglin, J. Dempsey, W. Hammer, F. d'Heurle and S. LaPlca, J. Appl. Phys. 51, 373 (1980).

27. J. E. Baglin. F. M. d'Heurle and C. S. Petersson, Appl. Phys. Lett. 36, 594 (1980).

28. R. D. Thompson, B. Y. Tsaur and K. N. Tu, Appl. Phys. Lett. 38, 535 (1981).

Table I. Summary of RBS analyses for 550 Å Ir/GaAs system.

Annealing conditions	Interface layer	Top layer	Overall [Ir]:[GaAs]
650°C 80 min.	[Ir]:[As] ≈ 1:2	[Ir]:[Ga] ≈ 1:1	1.5±0.1
700°C 16 min.	[Ir]:[As] ≈ 1:2	[Ir]:[As] ≈ 0.6:1	1.1±0.1

Table II. Summary of kinetics of solid phase reaction data for near noble metal/GaAs systems.

M/GaAs	Initial reaction temp. (°C)	Reaction Rate	Activation Energy ΔE(eV)	[M]:[GaAs]
Co/GaAs[a)]	<350°C	$\sim t^{1/2}$	1.70	2:1
Rh/GaAs[b)]	<300°C	$\sim t^{1/2}$	1.66	1.5:1
Ir/GaAs[c)]	~500°C	$\sim t^{1/2}$	3.15	1.1:1
Pt/GaAs[d)]	~300°C	$\sim t^{1/2}$	1.60	1.5:1

a) A. J. Yu, G. J. Galvin and J. W. Mayer, presented at Mat. Res. Soc. Mtg., May 15-18, 1986, Palo Alto, Ca.

b) K. M. Yu, unpublished data.

c) This study.

d) D. J. Coleman Jr., W. R. WIsseman and D. W. Shaw, Appl. Phys. Lett. 24, 355 (1974).

FIGURE CAPTIONS

Figure 1 RBS spectra from 550 Å Ir/GaAs samples as deposited (solid), annealed at 650°C for 80 min (cross) and at 700°C for 16 min (square).

Figure 2 Deconvolution of the RBS spectra from 550 Å Ir/GaAs samples annealed at 650°C for 80 min (a) and at 700°C for 16 min (b). The inserts show the structures of the corresponding samples and the backscattering geometry.

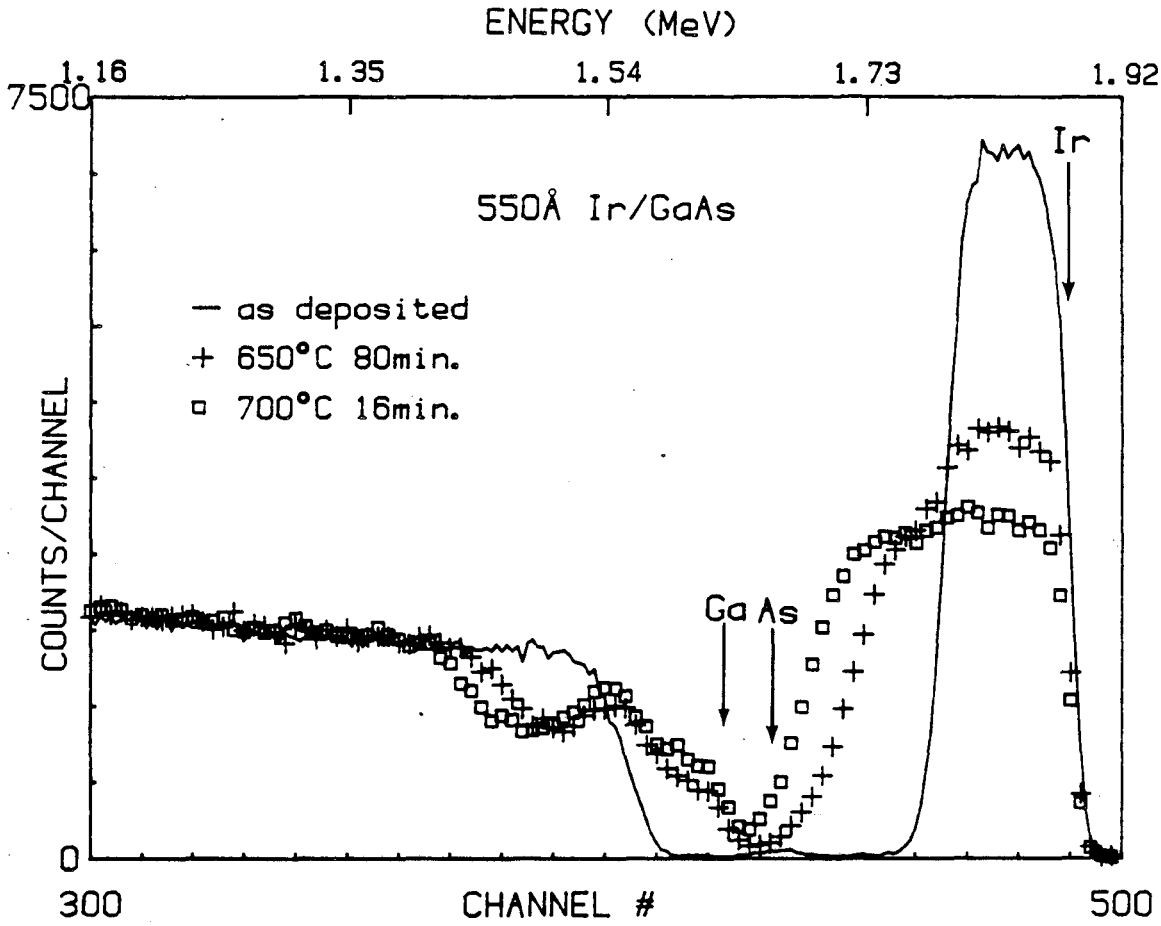
Figure 3 XRD spectra from 550 Å Ir/GaAs samples annealed at 650°C for 20 min (a), at 650°C for 80 min (b) and at 700°C for 16 min (c0).

Figure 4 Plots of the square of the reacted GaAs thickness measured by RBS in molecules/cm^2 as a function of the annealing time for different annealing temperatures.

Figure 5 Plot of ln D, the diffusivity calculated from the slopes of the plots in figure 4, versus the reciprocal of the annealing temperature in degree Kelvin.

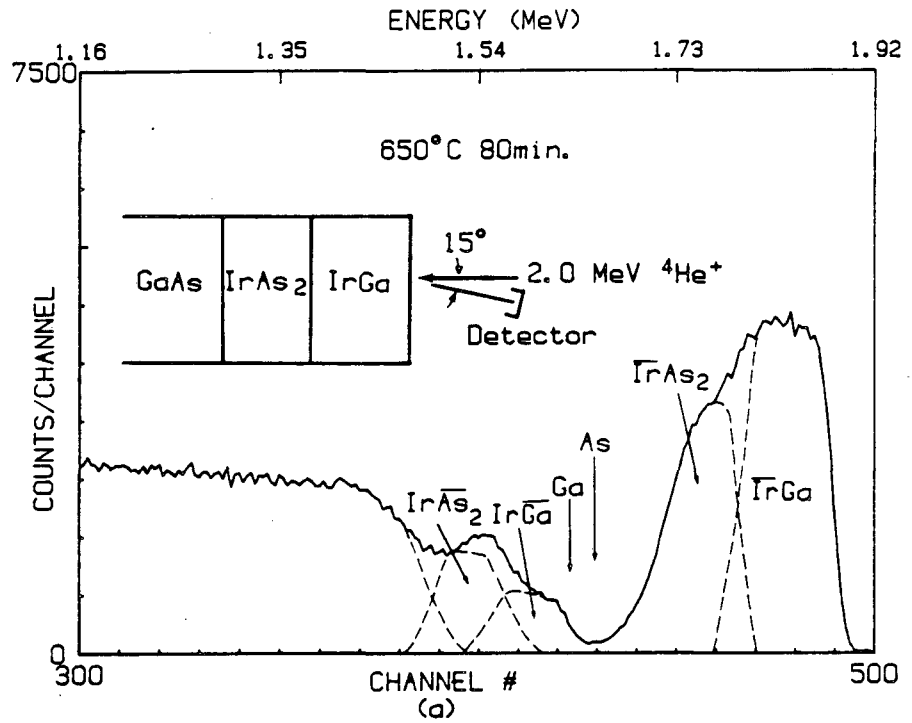
Figure 6 Transmission electron diffraction pattern from 100 Å Ir/GaAs after annealing at 600°C for 20 min with the corresponding TEM bright field image.

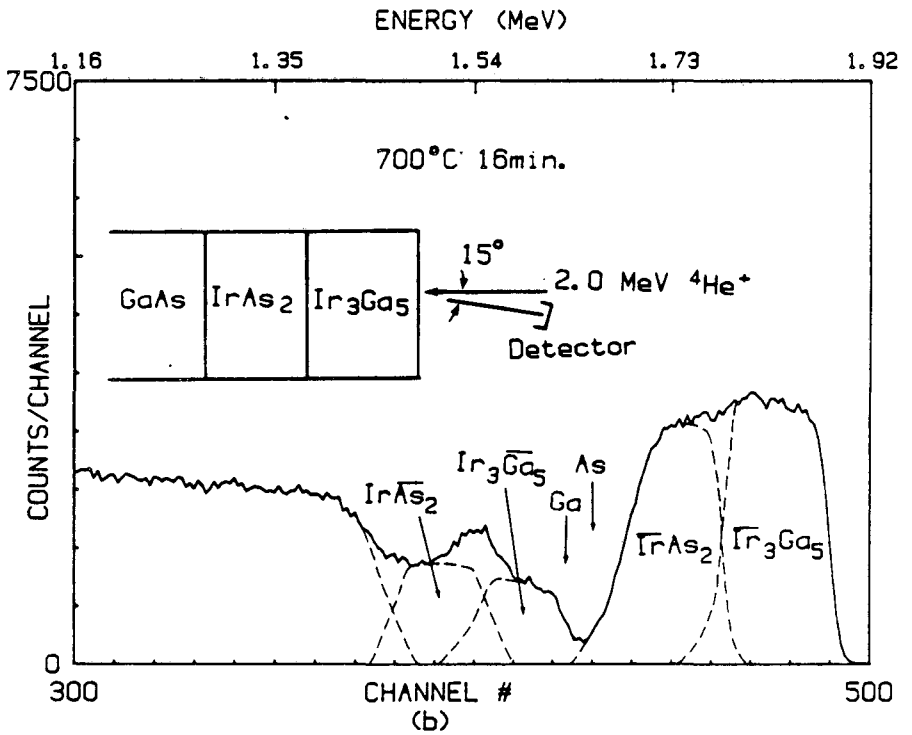
Figure 7 Glancing angle RBS spectrum from 100 Å Ir/GaAs sample annealed at 600°C for 20 min. The convolution of the spectrum is also shown in the figure (dashed spectrum). The insert shows the backscattering geometry.



XBL 869-3224

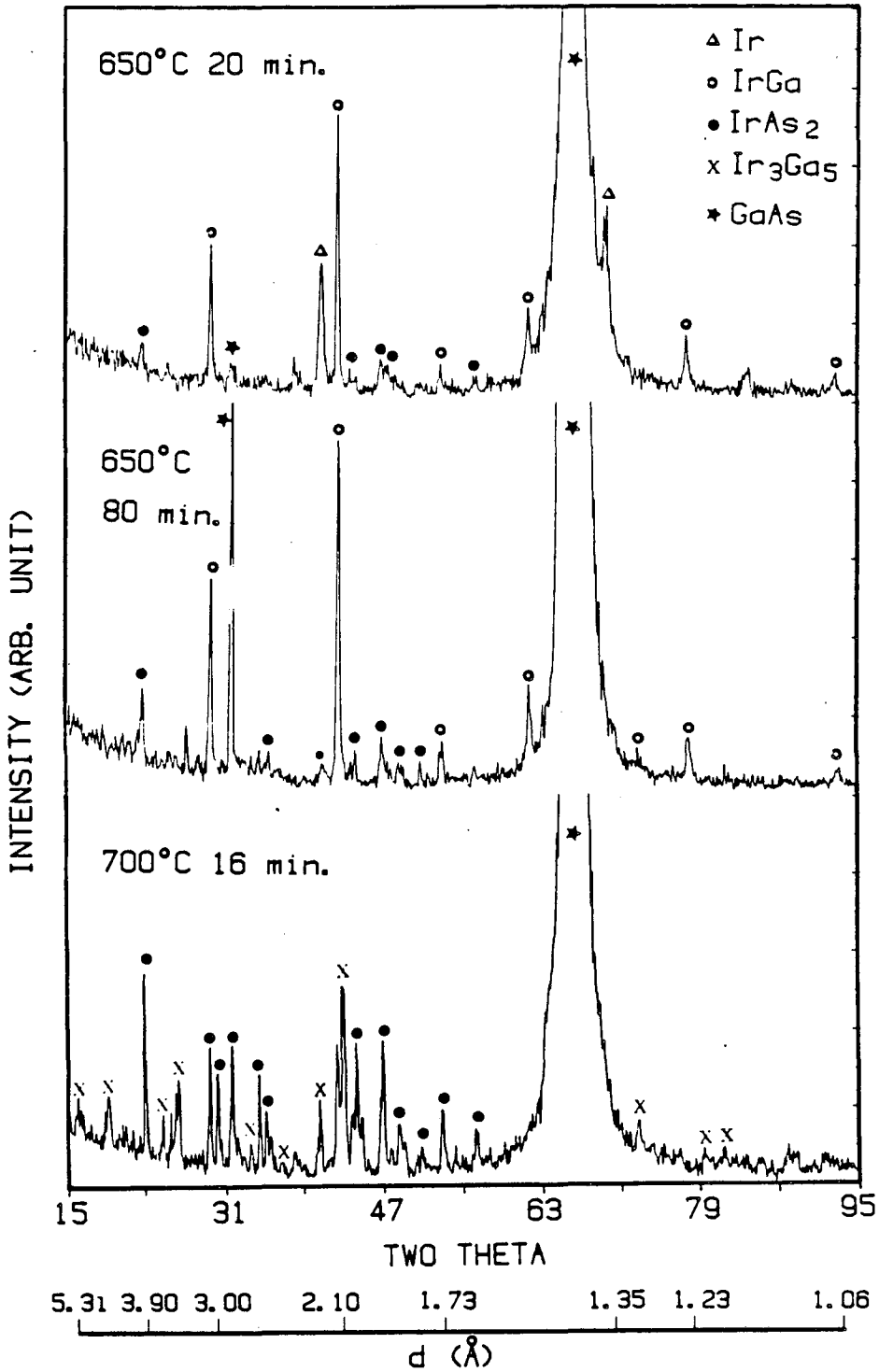
Fig. 1





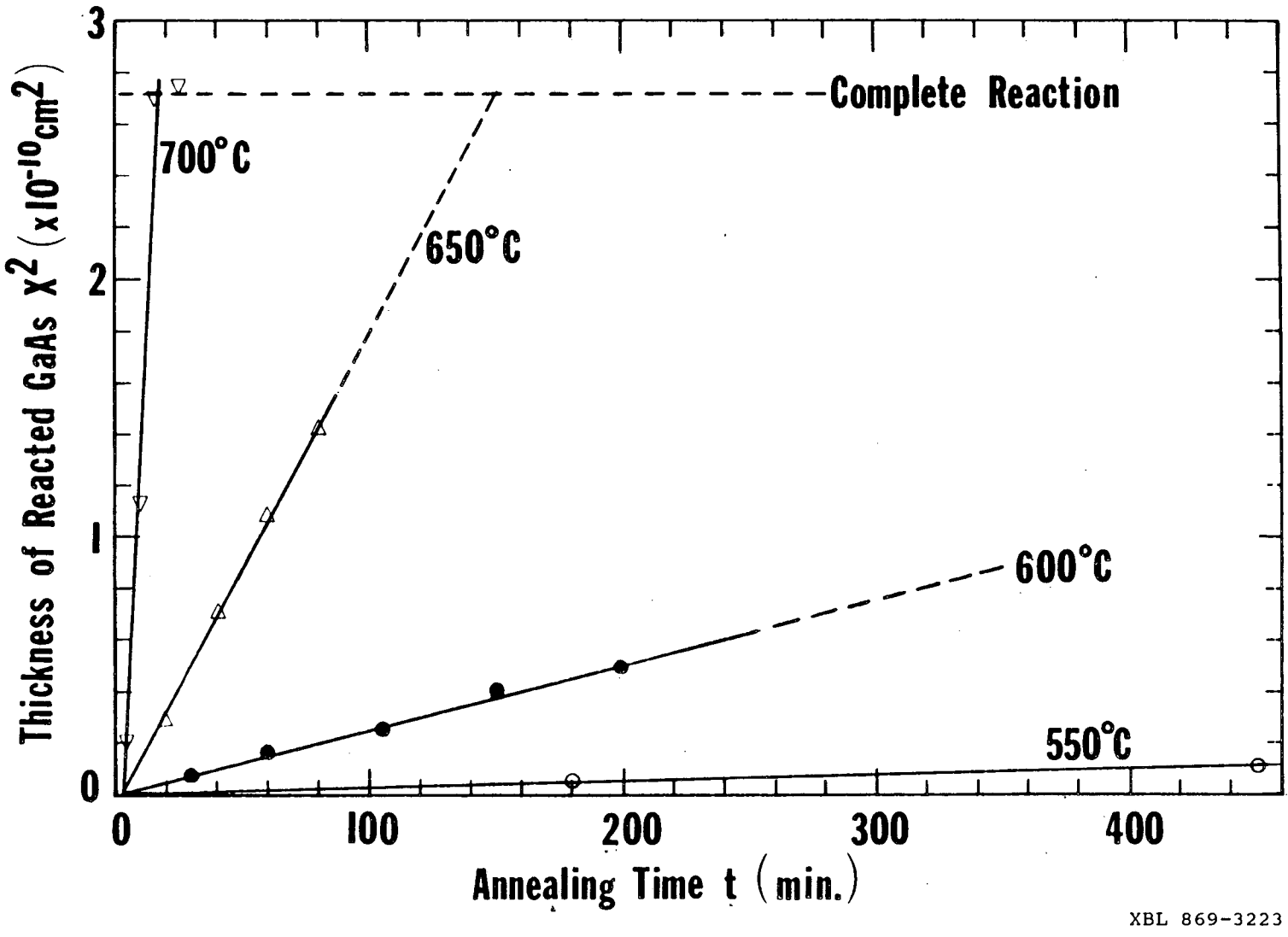
XBL 8612-4949

Fig. 2



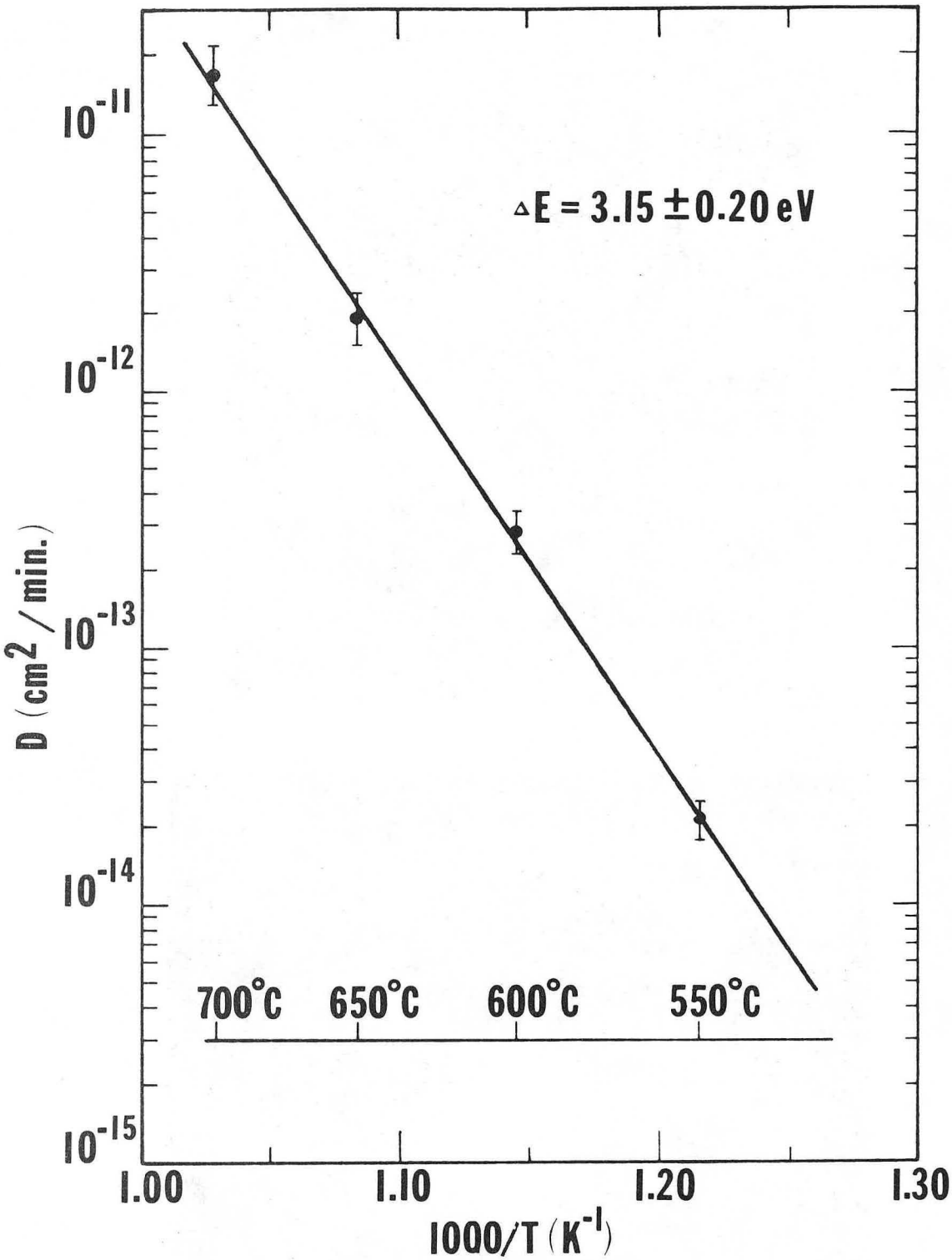
XBL 8612-4948

Fig. 3



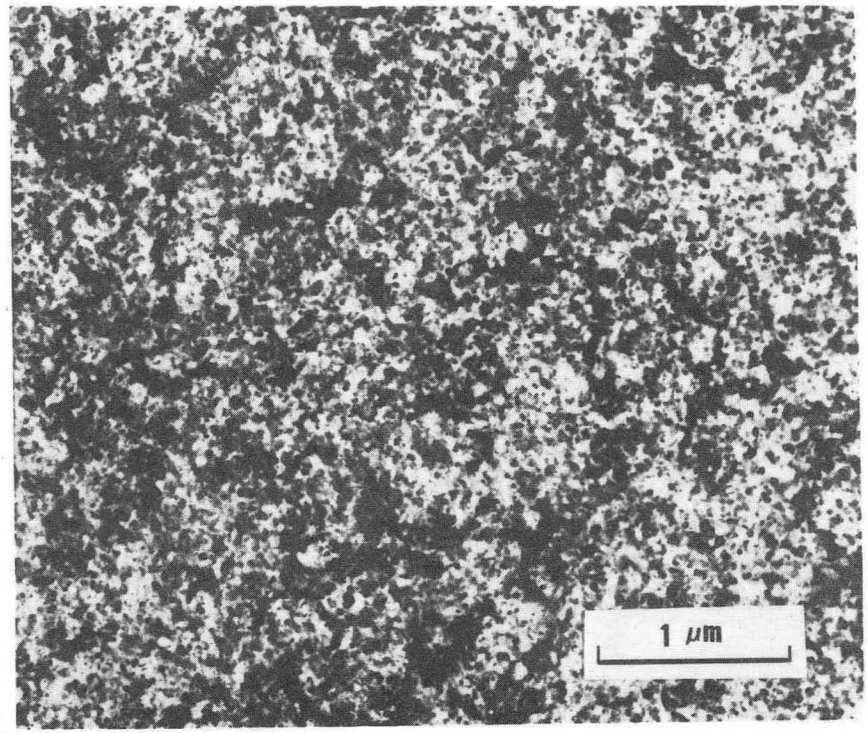
XBL 869-3223

Fig. 4



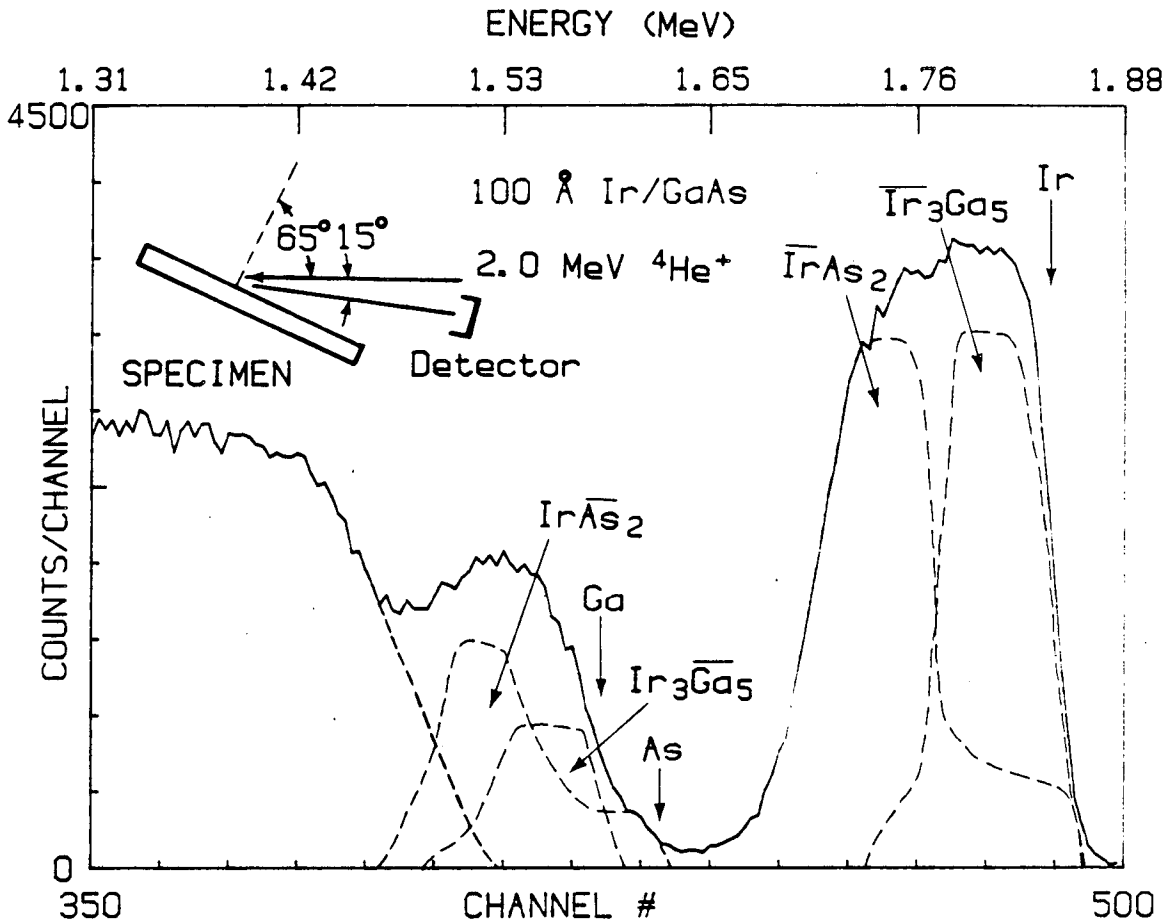
XBL 869-3225

Fig. 5



XBB 868-6001A

Fig. 6



XBL 8612-4947

Fig. 7

This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

LAWRENCE BERKELEY LABORATORY
TECHNICAL INFORMATION DEPARTMENT
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720