RADIATION-INDUCED PHOTOCONDUCTIVITY OF SILICON*

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ABSTRACT

The photoconductivity induced in zone-refined silicon doped with As, P, and Sb to resistivities in the range of 1 to 100 ohm-cm was studied after bombardment with 1.5 MeV and 45-50 MeV electrons. The dominant defect photoconductivity in all samples irradiated at 45-50 MeV is found to arise from an "energy band" extending from $\approx 1.5\mu$ to $\approx 4.0\mu$. A possible explanation of this energy band is given. Single well-defined defect energy levels dominate the photoconductivity of 1.5 MeV irradiated samples. Using stress-induced atomic and electronic reorientation together with annealing studies and correlating the results with previous electron paramagnetic resonance and infrared absorption experiments, levels located at E_c-0.54eV and E_c-0.39eV are indentified as arising from the divacancy defect.

1. INTRODUCTION

Photoconductivity (PC) offers an excellent method for measuring effects of radiation-induced defects in semiconductors. It can determine the energy levels of defects without heating the sample and annealing the defects in the process. Recent experiments (1) have shown that one can also determine the atomic and electronic configurations of the defects by using uniaxial stress and polarized light. This is accomplished by correlating these PC stress results with similar experiments employing electron paramagnetic resonance (EPR).

This paper is concerned with the study of the divacancy in n-type silicon using the above mentioned techniques. Therefore,

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*Supported by NASA under grant Ns G-290 and a NASA Traineeship to A. H. Kalma

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we shall correlate our results as they are presented with previously published EPR work (2,3) and infrared absorption (IR) work (4) on the divacancy. All samples used in this study were zone-refined.

2. EXPERIMENTAL RESULTS

A. 45 MeV vs. 1.5 MeV Electron Irradiation

The dominant defect photoconductivity observed in 1 to 100 ohm-cm samples irradiated with ≈ 45 MeV electrons arises not from single, well-defined energy levels, but from an "energy band" extending from $\approx 1.5\mu$ to $\approx 4.0\mu$. This is characterized by a gradual fall off of photoconductivity with increasing wavelength and is found in all samples independent of chemical species (As, P, and Sb) or concentration of dopant. The recovery of the "energy band" extends over a broad temperature range (100°C to above 340°C) and closely resembles what we have observed (4) in radiation-induced IR (which we have called near-edge absorption) for ≈ 45 MeV electron-irradiated silicon. High temperature ($\approx 160^{\circ}$C) stress experiments designed specifically to observe divacancies revealed no dichroism ($>$ 10%) of this band.

One explanation for the observed "energy band" is that defect complexes are formed which consist of clusters of vacancies, interstitials, and impurity atoms which destroy some of the periodicity of the lattice creating an allowed continuum of energy states in the forbidden gap thereby effectively decreasing the gap energy. This explanation of the decrease in the forbidden gap energy in irradiated silicon was first suggested in a schematic fashion in a paper by Vavilov (5).

Single defect energy levels can be observed in ≈ 45 MeV irradiated samples, but it is difficult to position them exactly or to study them due to the overriding effect of the "energy band". By constrast, in 1.5 MeV electron-irradiated silicon, very little of this "energy band" is observed and single levels

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predominate. These single levels can thus be studied much more easily. For the remainder of this paper, we shall concern ourselves with 1.5 MeV irradiations.

B. Annealing Behavior

Figure 1 presents the isochronal annealing behavior of a phosphorus-doped, 1 ohm-cm sample. All curves are normalized to the 1.24 eV point. Similar results have been obtained for arsenic and antimony-doped samples. The temperature at which the change from curve (a) to curve (b) takes place (168°C here) is not as meaningful as the Fermi level position. The temperature depends on the amount of damage in the sample initially and varies from $< 138^{\circ}$C to $> 200^{\circ}$C for initially similar samples. The Fermi level position where this change occurs appears to be $\approx E_c - 0.22$ eV. This position is close to the level below which the 1.8μ band is seen and above which the 3.3μ bands are seen in IR with monochromatic light (6). These bands have been indentified with the divacancy (4). On all samples, when an annealing temperature of $\approx 280^{\circ}$C was reached, the PC dropped down to curve (c). This is in the vicinity of annealing temperature of the divacancy (3).

When the Fermi level is below approximately E_c-0.22 eV, the only level observed is at E_c-0.54 eV. When, the Fermi-level is above E_c-0.22 eV, levels at E_c-0.36 eV, and E_c-0.39 eV are observed. In a few cases, the E_c-0.54 eV level can be seen giving rise to a small amount of photoconductivity. This effect is seen in Fig. 1. The level at E_c-0.54 eV disappears as the Fermi level moves slightly up from E_c-0.22 eV, also, a gradual decrease in photoconductivity extending from the absorption edge to $\approx$0.8 eV is observed in both conditions. This could be due to the small amount of disorder caused by 1.5 MeV electrons.

C. High Temperature Stress Studies

At elevated temperatures ($\approx 160^{\circ}$C) there is enough thermal energy available for the atomic configuration of the divacancy to reorient (3). Stress at 160°C followed by cooling with the stress on and removal of the stress when the sample reaches room temperature freezes in the atomic reorientation but allows the electronic configuration to redistribute to its unstressed state. Fig. 2 shows the results of such a stress on the E_c-0.39 eV level. Curves (a) and (b) are obtained by subtracting the photoconductivity due to the E_c-0.36 and E_c-0.22 eV levels from the total curve. This gives the photoconductivity due to the E_c-0.39 eV level alone. Further results of high temperature stress are given in Table I.

TABLE I

Dichroism Results on 1 Ohm-cm Silicon Stressed at ≈160°C.

Doping	Stress (kg/cm^2)	Stress direction	IR direction	E_c-0.39eV	E_c-0.54eV
As	1540	[011]	[100]	1.23	____
As	1540	[011]	$[0\bar{1}1]$	1.13	____
Sb	1450	[011]	[100]	1.16	____
P	1770	[011]	[100]	1.17	1.25
P	1600	[100]	[011]	1.00	1.01

The dichroisms quoted are in all cases ±.05. These all agree in sense and within experimental error in magnitude with the ones found on the divacancy in EPR (3) and on the 1.8μ and 3.3μ bands identified with the divacancy in IR (4). It should be noted that stress in the [100] direction produces no significant dichroism. This agrees with the divacancy model where the atomic symmetry is around a ⟨111⟩ axis. These four axes all make equal angles with [100] and are all equivalent for stress along that direction.

D. Low Temperature Stress Studies

If the sample is stressed at liquid nitrogen temperature and the stress left on during measurement, the atomic configuration cannot reorient but the electronic one can. Table II presents the results of such low temperature stress.

TABLE II

Dichroism Results on 1 Ohm-cm Silicon Samples Stressed at 78°K.

Doping	Stress (kg/cm^2)	Stress direction	IR direction	E_c-0.39 eV	E_c-0.54eV
P	1230	[100]	[011]	.91	____
P	1200	[011]	[100]	1.17	1.17
P	1230	[100]	[011]	.90	____
As	1130	[011]	[100]	1.21	____
As	1130	[011]	$[0\bar{1}1]$	1.14	____
As	1390	[011]	[100]	____	1.10
As*	1390	[011]	[100]	1.14	1.10

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*Measured with white light on the sample.

Again, these agree in sense with what has been found previously in EPR (3) and IR (4) although the magnitude in most cases is smaller here. As soon as the stress is released, this dichroism disappears as it should since it is only frozen in below ≈ 20°K.

E. Annealing of the High Temperature Stress-Induced Dichroism

Fig. 3 shows the isochronal annealing of the high temperature stress dichroism found in EPR (3), IR (4), and this PC study. The dichroism of the two PC levels disappears at the same temperature as that of the divacancy (3,4). This adds futher evidence that the E_c-0.39eV and E_c-0.54eV levels are associated with the divacancy.

F. Effect of White Light on the Photoconductivity

As was mentioned previously, the 1.8μ and 3.3μ bands are not seen at the same time in IR where monochromatic light strikes the sample (6). It has been observed that if the Fermi level is below E_c-0.21eV position where only the 1.8μ band is observed and the spectrometer is set up so that white light strikes the sample, both bands are seen (7). Figure 4 shows the effect on the photoconductivity of white light on a sample where the Fermi level was deeper than E_c-0.22eV. Both the E_c-0.39eV and E_c-0.54eV levels are seen. The E_c-0.54eV level causes much more photoconductivity in this condition than when the E_c-0.39eV level is observed with no light on the sample (Fermi level above E_c-0.22eV).

3. SUMMARY AND CONCLUSIONS

Based on the similarity in annealing and stress-induced reorientation, both atomic and electronic, of the E_c-0.54eV and E_c-0.39eV levels observed in PC and the divacancy previously studied by EPR and IR, we would argue that these two levels arise from the divacancy. An identification of the nature of the transitions is not possible as yet. Nor can we build upon or change the speculative suggestions put forward by Cheng et al. (4). Both levels are transitions from localized states in the forbidden gap to the conduction band (this was implied already by identifying them as E_c-0.54eV and E_c-.39eV) as opposed to being to a localized "molecular" state.

A final note is that the level located at E_c-0.36eV occurs very close to the E_c-0.39eV level. As such, it is almost impossible to study it for dichroism. The other levels observed in this study did not exhibit dichroism characteristic of the divacancy and therefore can be ruled out as arising from the defect.

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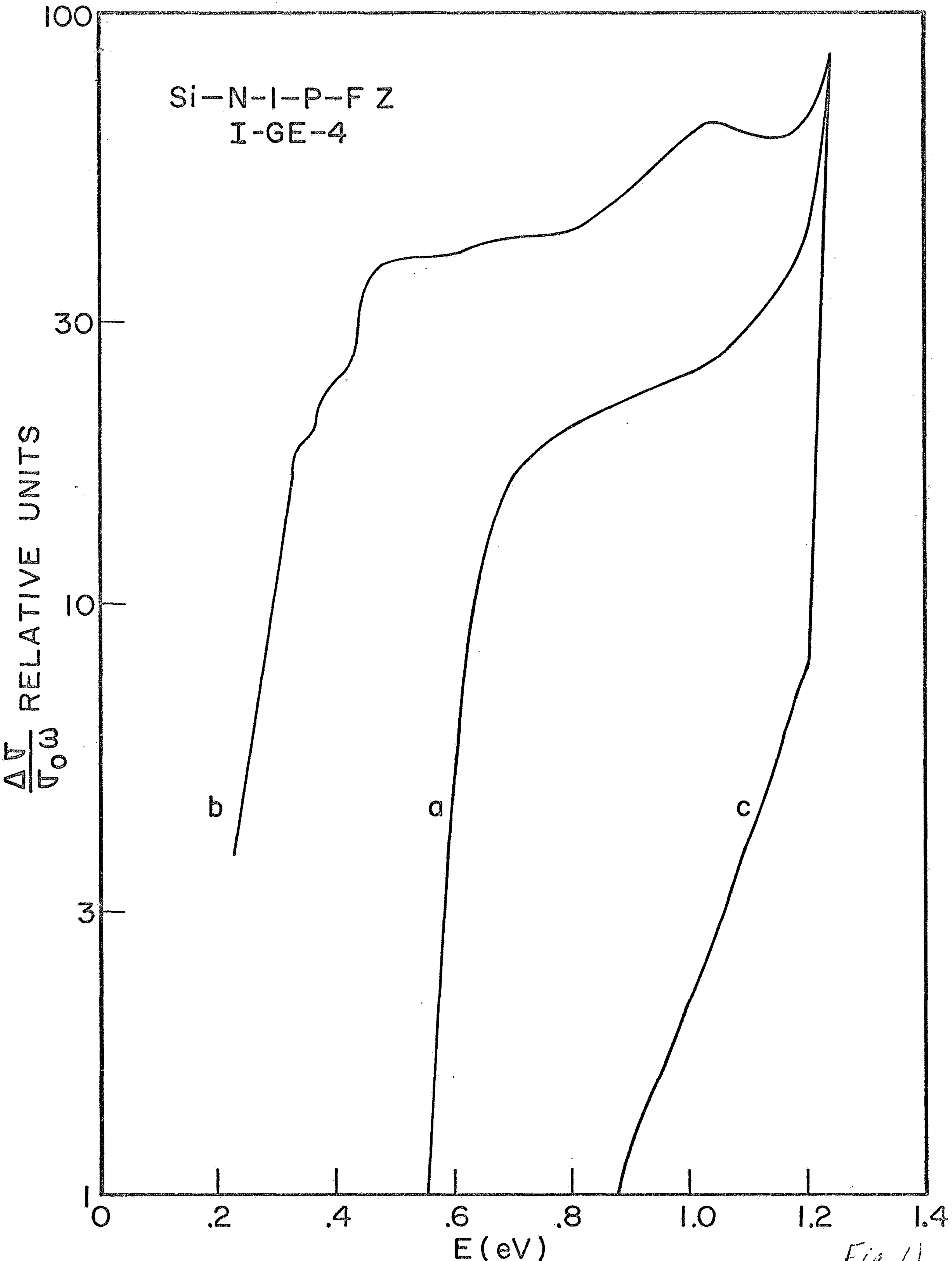
FIGURE CAPTIONS

Figure 1. Isochronal annealing of P-doped, 1 ohm-cm silicon irradiated with 4 x 10^{16} elec./cm^2 at 1.5 MeV. (a) no anneal-138°C, (b) 168°C - 242°C, (c) 279°C. 15 minutes at each temperature.

Figure 2. Dichroism of the E_c-0.39eV level after high temperature stress. Arsenic doped, 1 ohm-cm silicon irradiated with 2 x 10^{16} elec./cm^2 at 1.5 MeV. 1540 kg/cm^2 stress applied at 157°C for 15 minutes.

Figure 3. Isochronal annealing of [011] stress-induced dichroisms of photoconductivity and infrared. Also shown is the anneal of the stress-induced divacancy alignment as studied by EPR (3). 15 minutes at each T_a.

Figure 4. Effect of light on highly irradiated, n-type silicon. Arsenic-doped, 1 ohm-cm silicon irradiated with 10^{17} elec/cm^2 at 1.5 MeV.


Si—N—I—P—F Z
I-GE-4
$\frac{\Delta\sigma}{\sigma_0\omega}$ RELATIVE UNITS
100
30
10
3
1
0
.2
.4
.6
.8
1.0
1.2
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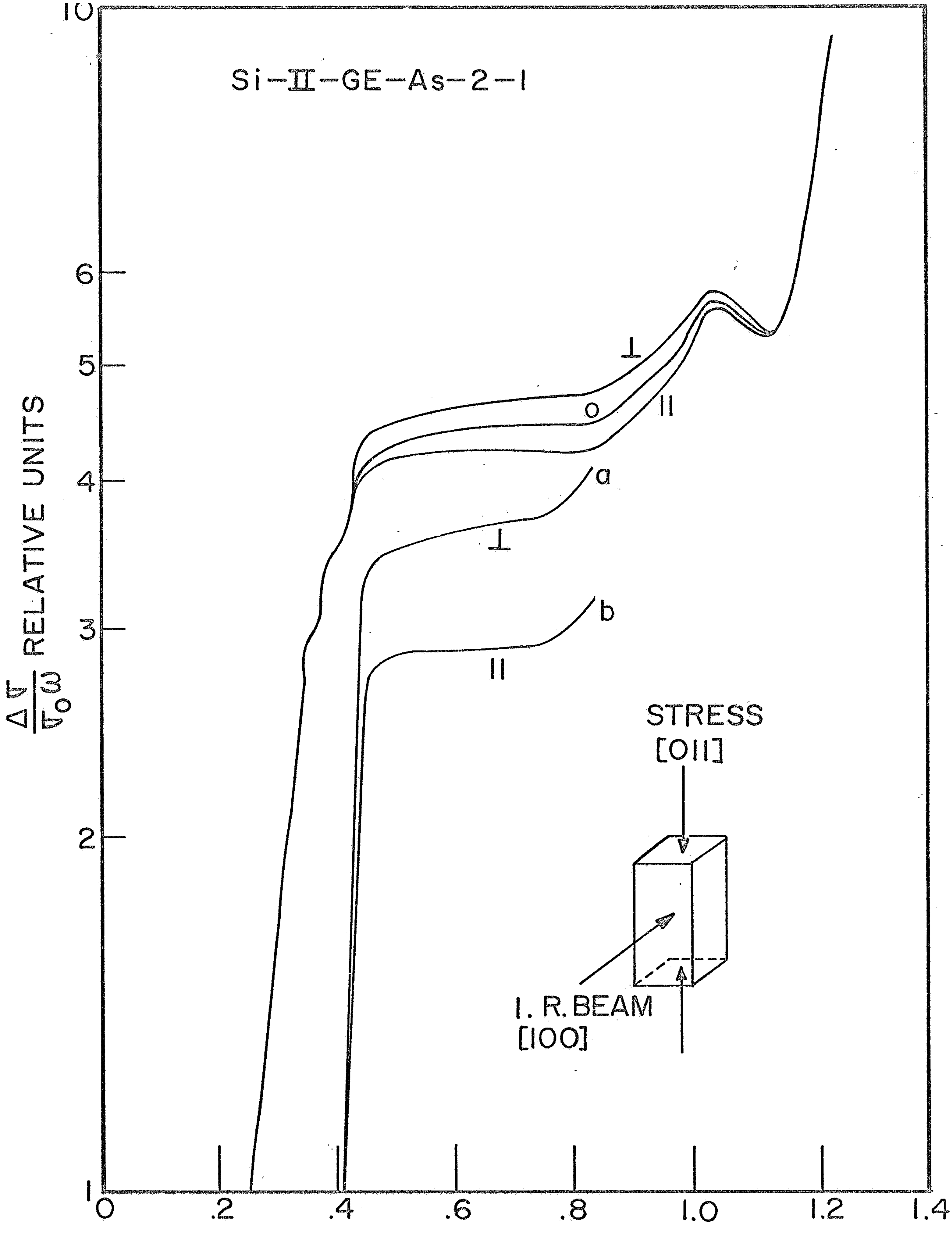
E(eV)
b
a
c

Fig 1.)


Si—II—GE—As—2—1
10
6
5
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3
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$\frac{\Delta\sigma}{\sigma_0}(\omega)$ RELATIVE UNITS
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.2
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1.0
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E (eV)
⊥
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II
STRESS
[011]
I. R. BEAM
[100]

Fig 2.

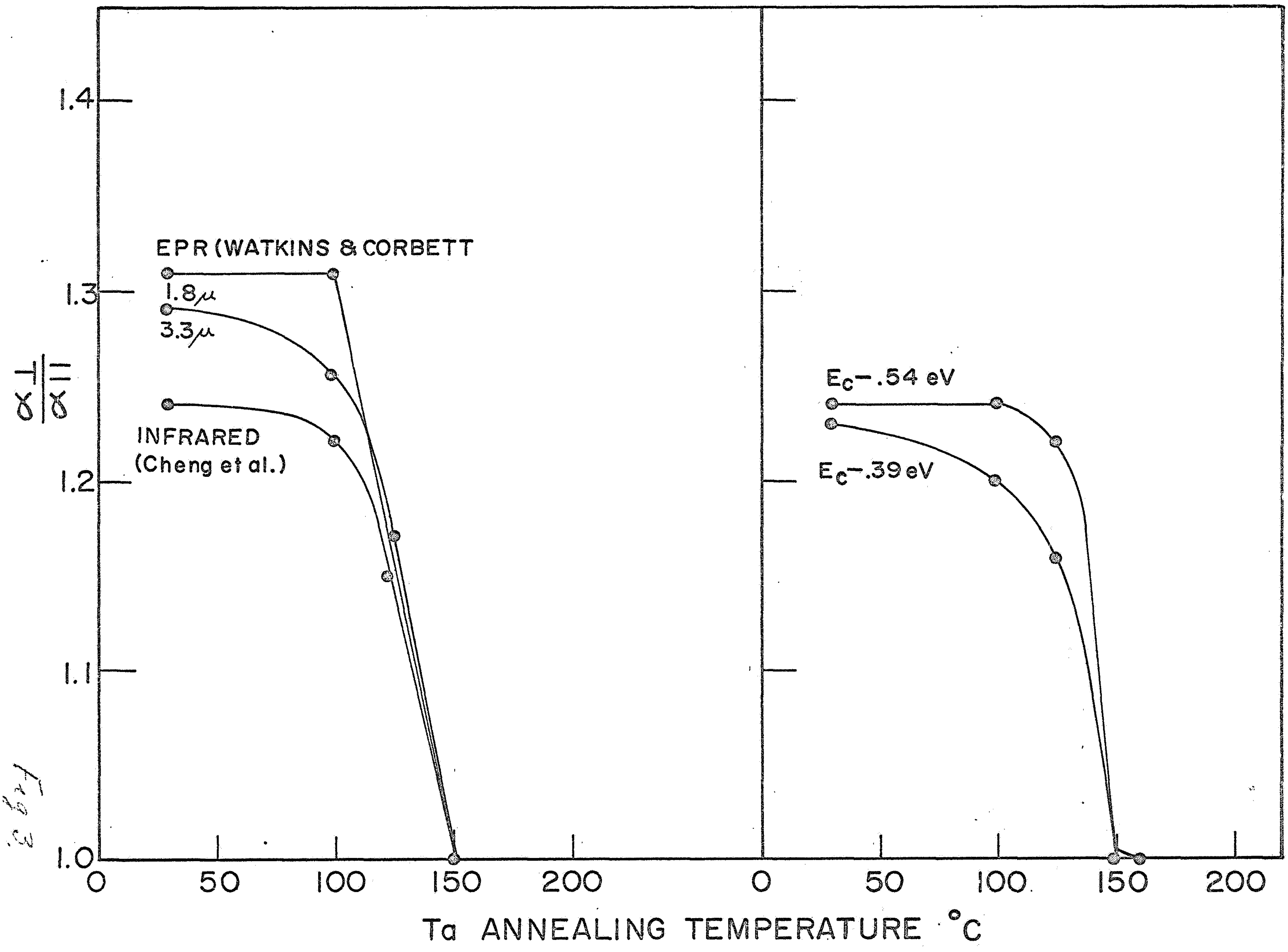
$\frac{\alpha_{\perp}}{\alpha_{\parallel}}$
1.4
1.3
1.2
1.1
1.0
EPR (WATKINS & CORBETT
1.8μ
3.3μ
INFRARED
(Cheng et al.)
Ec−.54 eV
Ec−.39 eV
0
50
100
150
200
Ta ANNEALING TEMPERATURE °C

Fig 3.

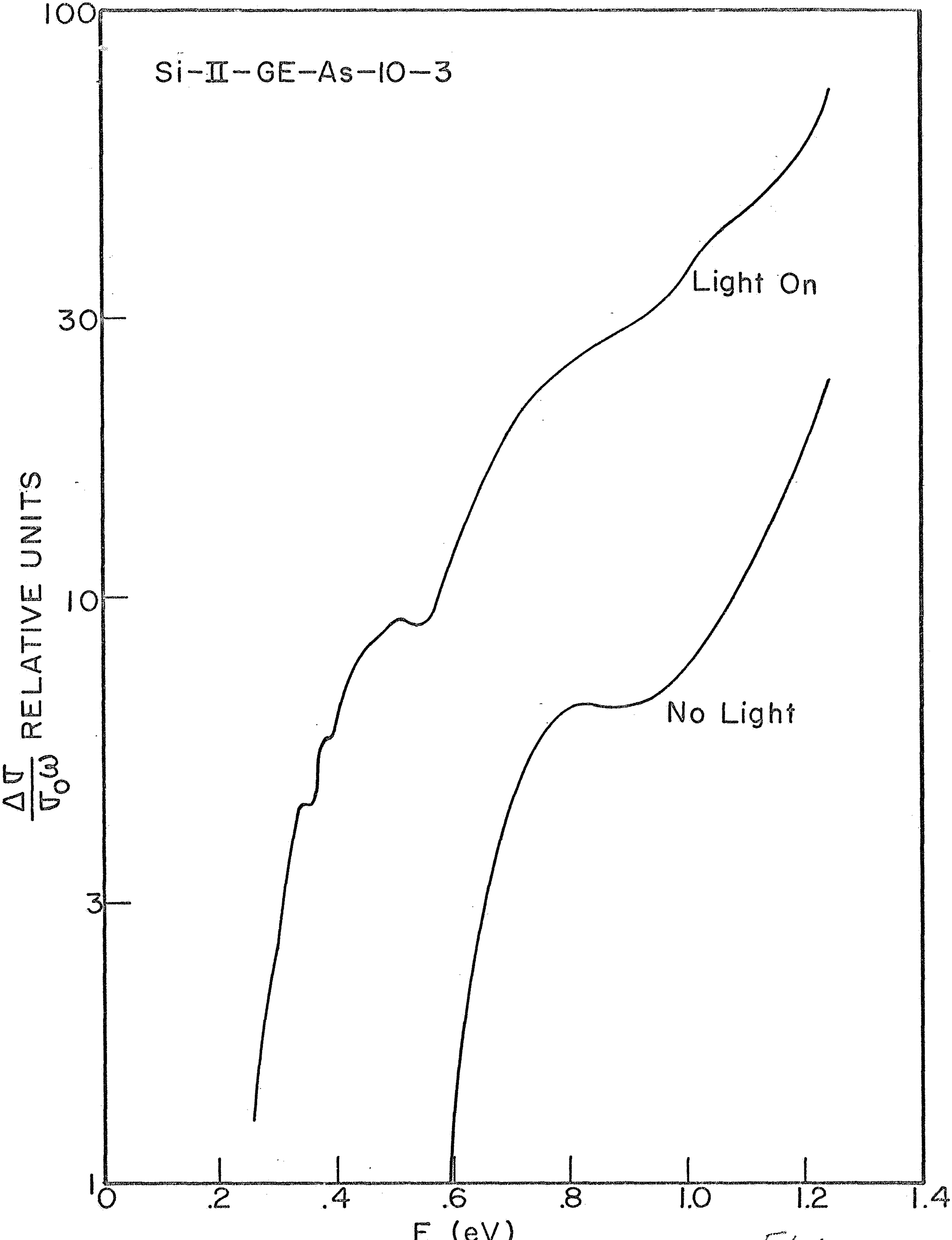
Si-II-GE-As-10-3
Light On
No Light
100
30
10
3
1
0
.2
.4
.6
.8
1.0
1.2
1.4
$\frac{\Delta\sigma}{\sigma_0(\omega)}$ RELATIVE UNITS
E (eV)

Fig 4.1