PRAMANA
— journal of
physics

Vol. 44, No. 1,
January 1995
pp. 19–32

Microwave conductivity studies on some semiconductors

V SUBRAMANIAN, V R K MURTHY and J SOBHANADRI
Department of Physics, Indian Institute of Technology, Madras 600036, India

MS received 21 September 1994

Abstract. The cavity perturbation technique is employed for the characterisation of semiconductors at microwave frequency for its conductivity. Temperature variation of microwave conductivity studies provide the information regarding the band gap, scattering parameter and impurity ionization energy. Change in the real part of the dielectric permittivity with conductivity indicates the change in the momentum relaxation time.

Keywords. Cavity perturbation technique; silicon; microwave conductivity; momentum relaxation time.

PACS Nos 72·20; 77·00

1. Introduction

Application of microwave techniques to characterize semiconductors is steadily gaining importance for variety of reasons. The study of complex dielectric permittivity of semiconductors at microwave frequencies is useful in additionally estimating the momentum relaxation time and effective mass. Though the conventional DC conductivity technique is simpler and easier to characterize the semiconductor for its bandgap, scattering phenomena, activation energy etc., the microwave technique is superior since it removes the contact potential problem, giving all the information that the DC technique provides and also giving information about the relaxation time of the carriers. As early as 1960, microwave techniques have been used to characterize the semiconductors for its conductivity and lifetime. Transmission and reflection techniques have been employed for these studies. Henisch and Zucker [1] in 1956 developed an experimental arrangement to measure the conductivity and lifetime at 9 MHz using a resonant cavity. In 1959, Ramsa *et al* [2] utilized the reflection technique in the microwave frequency region. Employing the cavity resonance technique for semiconductors at microwave frequencies had been proposed by Montgomery [3] in 1947. Recently various versions of microwave measurement technique are reported for the characterization of Si[4–6], GaAs[7], CdS[8], ZnS[9], HgCdTe[10], InP[11] and Zn_3P_2[12].

The microwave techniques utilized for the characterization of semiconductors can be classified broadly into reflection [13–14], transmission [15] and cavity resonance techniques [16–19]. Among these, cavity resonance technique is considered to be the most sensitive and does not require large amount of samples. Cavity perturbation technique is one such technique and is widely used in the dielectric measurements of liquids and solids [20–21]. This technique is also used for the transient analysis of certain liquid samples like cyclohexanaone to monitor the reaction kinetics [22] and also to monitor the minority carrier lifetime in semiconductors [12].

The analysis of cavity perturbation technique assumes that the cavity is a lumped resonant circuit resembling the parallel or series LCR depending upon reflection or transmission type respectively. Murthy and Raman [21] utilized this assumption on a reflection type TE_{10n} mode cavity and derived an expression for the measurement of dielectric parameter when the sample fully occupies the '*b*' dimension of the rectangular cavity at the electric field maximum. If the sample does not fully occupy the '*b*' dimension of the cavity, the available formulae cannot be used. Recently, Lehndroff [23] has arrived at a correction factor involving the depolarization factor (can be used only for cylindrical samples) due to the reduction in the sample size. But this correction factor cannot be used for semiconductor samples due to the sample size requirement. Therefore the cavity perturbation technique is employed to study the relative variation in conductivity.

In this paper, the cavity perturbation technique is used in the characterization of some semiconductor samples (single and polycrystalline silicon and GaAs) for its temperature variation of conductivity (300–500 K) at 9 GHz. From this data the band gap, scattering mechanism etc. are studied as in the case of temperature variation of DC conductivity. The variation of momentum relaxation time with conductivity is also reported for a single crystal silicon samples.

2. Sample

The samples used in the present study are listed in table 1. The carrier concentration of the silicon samples is in the range of 10^{13}–10^{16}/cm^3. The single crystal gallium arsenide is an *n*-type semi-insulating sample with resistivity around 12000 Ω-cm. Among the six silicon samples, three samples are single crystal and other three are polysilicon of different grain sizes. The silicon samples are prepared by Czeckrolski technique and supplied by Metkem, India.

3. Theory

The carrier motion in a semiconductor acted upon by an electromagnetic field of angular frequency ω is given by Drude–Zener theory [24–25],

$$m^* \frac{dv}{dt} = eEe^{-j\omega t} - \frac{m^* v}{\tau(v)} \tag{1}$$

Table 1. List of samples under study.

Sample	Type	ρ(Ω-cm)	Grain size (μm)
Silicon-A	*p*	320	Single
B	*p*	135	Single
C	*n*	80	Single
E	*n*	120	Single
K1	*P*	1·9	150
M2	*n*	120–240	800
GaAs-R	*n*	12000	Single

where $Ee^{-j\omega t}$ is the applied field, m^*, the effective mass, v, the velocity of carrier and $\tau(v)$ is the momentum relaxation time (a function of velocity). The current density due to the application of electromagnetic field is given by,

$$J = J_i + J_o \tag{2}$$

where n is the carrier concentration, σ is the conductivity at microwave frequency,

$$J_i = \sum \frac{ne^2\tau(v)Ee^{j\omega t}}{m^*[1+\omega^2\tau^2(v)]} = \sigma Ee^{j\omega t} \tag{3}$$

and

$$J_o = \sum \omega \in Ee^{j\omega t} - \frac{ne^2\tau^2(v)\omega Ee^{j\omega t}}{m^*[1+\omega^2\tau^2(v)]} \tag{4}$$

J_i is the in-phase component of current density and gives the conductivity at ω. J_o is the out-of-phase component and is the resultant of dielectric current and out-of-phase carrier current. This out-of-phase carrier current changes the effective dielectric permittivity by $\Delta\varepsilon$. The AC conductivity is now given by,

$$\sigma = \sum \frac{ne^2\tau(v)}{m^*[1+\omega^2\tau(v)^2]} = \frac{\sigma_{DC}}{[1+\omega^2\tau(v)^2]} \tag{5}$$

For τ in the other of 10^{-13} s [25], at 10 GHz, the values of σ and σ_{DC} are same. For a single relaxation time, the complex dielectric permittivity of a semiconductor is given by

$$\varepsilon^* = \varepsilon' - j\varepsilon'' = \varepsilon' - j\sigma\omega\varepsilon_0 \tag{6}$$

where ε' is the dielectric constant and ε'' is the dielectric loss.

The change in the dielectric permittivity due to the out-of-phase carrier current is given by

$$\Delta\varepsilon' = -\frac{\sigma\tau}{\varepsilon_0}. \tag{7}$$

The complex dielectric permittivity therefore gives the value of the conductivity at microwave frequencies and the change in the dielectric constant at DC. Benedict and Shockley [26] showed that the (7) can be used to evaluate the momentum relaxation time of the carriers.

The cavity perturbation technique is used to calculate the complex dielectric permittivity of semiconductors. As mentioned earlier, it is very difficult to measure the absolute value of complex dielectric permittivity and therefore, the relative variation of complex dielectric permittivity is measured by varying the temperature. The complex dielectric permittivity is calculated from the change in the resonance frequency and the quality factor of the cavity due to the introduction of the semiconductor sample in an electric field maximum. While the shift in the resonance frequency is related to ε', the change in the quality factor is attributed to ε''

$$(\varepsilon' - 1) \propto \left(\frac{f_0^2 - f_1^2}{f_1^2}\right) \tag{8}$$

and

$$\varepsilon'' \propto \left(\frac{1}{Q_1} - \frac{1}{Q_0}\right) \tag{9}$$

where f_0 and f_1 are the resonance frequency of the empty and sample loaded cavity, Q_0 and Q_1 are the quality factors of empty and sample loaded cavity. From (6), it is obvious that the conductivity is indirectly proportional to the change in the Q-factor of the cavity

$$\sigma \propto \Delta\left(\frac{1}{Q}\right). \tag{10}$$

4. Experimental

The block diagram of the experimental arrangement is shown figure 1. HP8720A microwave vector network analyser output port is connected to a TE_{103} mode reflection type cavity by means of a flexible coaxial connector. The resonance frequency of the empty cavity is 9·158 GHz and the loaded quality factor is 2800. The resonance curve is shown in figure 2. The samples are loaded in the sample holder made with teflon. The resonance frequency of the cavity with empty sample holder is 9·082 GHz. The cavity has a provision for fixing the sample holder at the centre of the cavity. The sample can be illuminated with light of energy greater than the band gap. The temperature of the cavity is varied from 300 to 550 K and monitored by a computer. Network analyzer and the digital nanovoltmeter (used to monitor the thermocouple voltage) are connected to the computer through IEEE 488 interface bus for the data transfer and temperature controlling.

Network analyser's port parameters are calibrated up to the cavity connection using a standard waveguide calibration kit provided by the Hewlett Packard. The

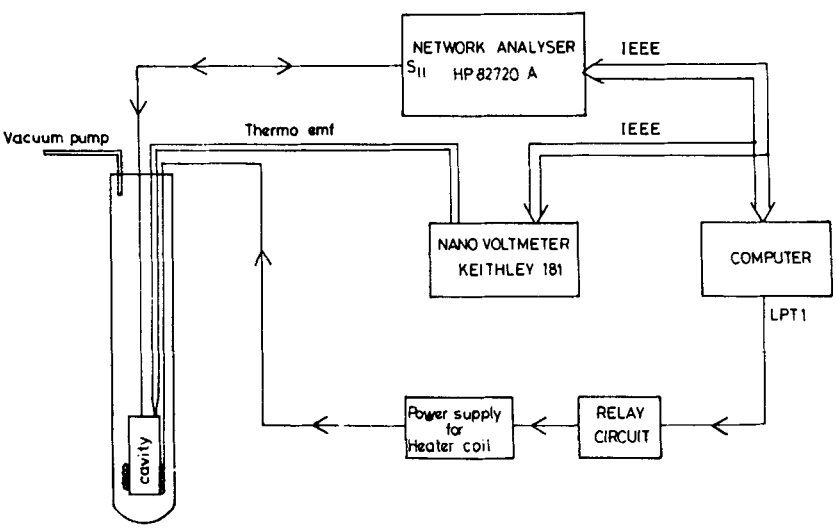

Figure 1. Block diagram of the experimental arrangement to measure the microwave conductivity.

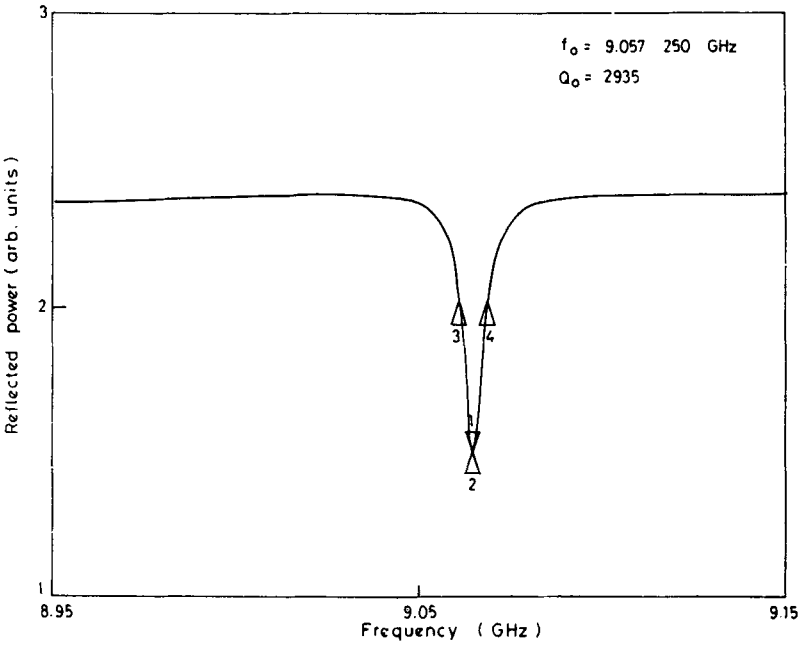

Figure 2. Resonance curve of the empty cavity.

empty cavity (along with the sample holder) is connected and the temperature is varied to get the reference data on the shift in resonance frequency and change in the quality factor with temperature. Figure 3 shows the change in the resonance frequency and quality factor. All the data taken for samples are normalized with these values.

The accuracies in the measurement of resonance frequency and quality factor are $\pm$ 10 kHz and $\pm$ 10 respectively.

5. Results and discussion

5.1 *Temperature variation of conductivity*

The temperature variation studies on conductivity and dielectric constant are already reported earlier in 1960s and 1970s. But it was not pursued further which may be due to lack of sensitive experimental arrangement and difficulty in the measurement. Bhar [24] had reported the variation of microwave conductivity with temperature in two single crystal silicon samples (1000 and 143 Ω-cm) and similar studies on three single crystal silicon samples (0·5, 40, 170 Ω-cm) are reported by Natarajan *et al* [27]. Both these papers utilized the reflection technique. Though both these papers show similar graphs and give an interpretation with extrinsic and intrinsic conductions, the band gaps from the intrinsic region are not evaluated. The difficulty in getting the band gap value may be due to lack of sensitive experimental arrangement to compensate the variation of reflectivity from the empty waveguide with temperature. With the extension of cavity perturbation technique and availability of vector network

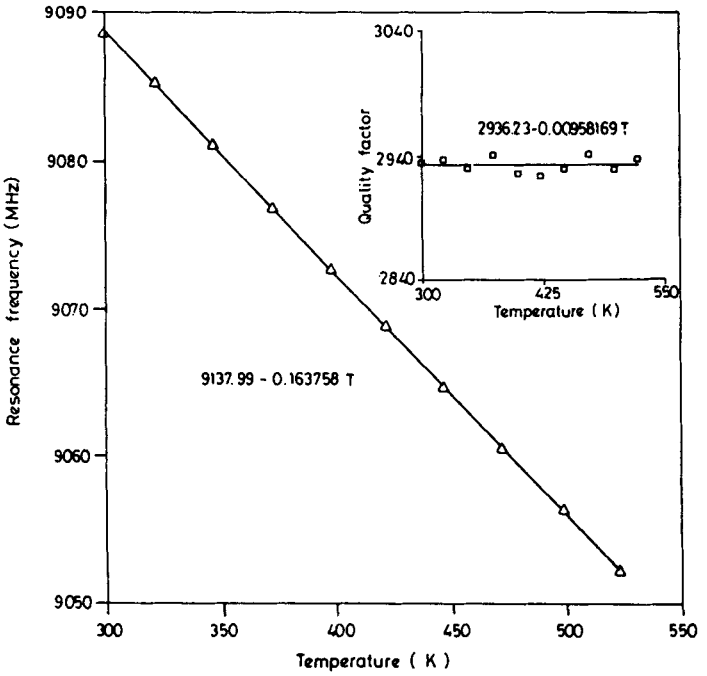

Figure 3. Variation of resonance frequency with temperature. Inset: Variation of quality factor with temperature.

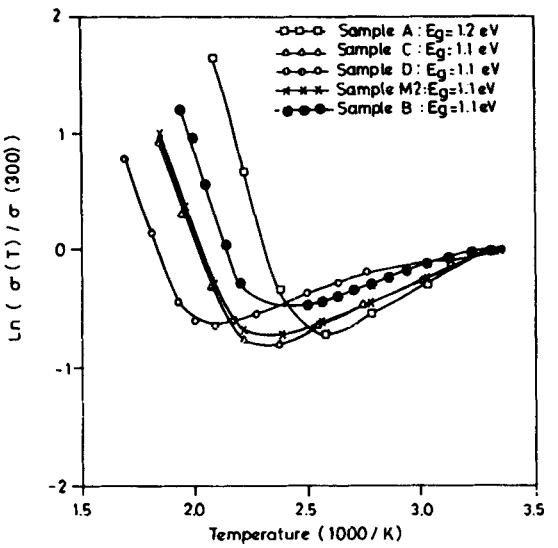

Figure 4. Variation of microwave conductivity with temperature for silicon samples-A, B, C, E, and M2.

analysers, it is possible to study accurately the variation of complex dielectric permittivity with temperature or illumination intensity.

Figures 4–6 give the variation of microwave conductivity with temperature for silicon and gallium arsenide samples. The slope of the plot between $\ln(\sigma(T)/\sigma(300))$ and $1/T$ gives the band gap. Table 2 presents the results on the band gap of silicon and gallium arsenide. The temperature variation of conductivity observed for sample-K1 (figure 6) shows that the sample has not reached the intrinsic region and the region from 300–400 K still exhibits the active nature of deep impurity centre having the activation energy 0·28 eV below conduction band. Paul Marusk *et al* [28] have reported the activation energy of 0·216 eV in a 7 Ω-cm polysilicon sample of grain size 1000 μm using DC resistivity data. The temperature region 400–500 K represents the participation of lattice scattering and impurity centre or may indicate the carrier saturation region.

5.2 *Temperature variation study of dielectric permittivity*

As given by (7), the dielectric permittivity (ε') also changes with the conductivity of the semiconductor. As the conductivity increases, the $\Delta\varepsilon'$ also increases. The negative sign in (7) indicates that the absolute value of the dielectric permittivity decreases with increase in σ or τ. The change in the dielectric permittivity due to carrier motion was experimentally observed by Benedict [29] for a germanium sample as 0·1% having resistivity of 1000 Ω-cm. Cardona *et al* [30] had also observed the change in a 1 MΩ-cm silicon sample as approximately 1% for the change in the temperature from 50 to 200 K and predicted even higher change at temperatures above 300 K.

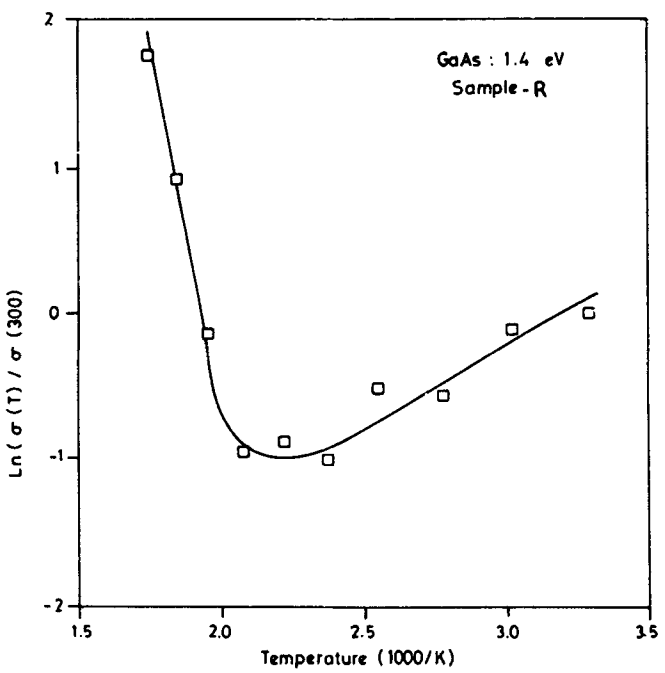

Figure 5. Variation of microwave conductivity with temperature for semi-insulating GaAs sample-R.

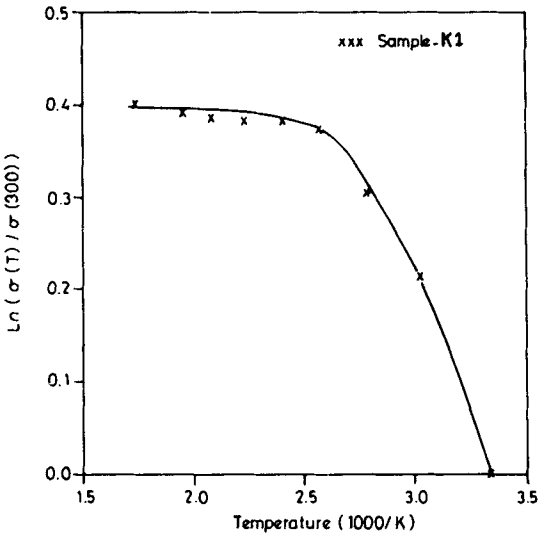

Figure 6. Variation of microwave conductivity with temperature for silicon sample-K1. The variation shows that the extrinsic conduction region due to the impurity centre located at 0·28 eV below the conduction band and the subsequent carrier saturation region.

Table 2. The energy gap calculated in silicon and gallium arsenide samples using the temperature variation of conductivity at microwave frequency.

Sample	Energy gap (eV)
Silicon-A	1·2
Silicon-B	1·1
Silicon-C	1·1
Silicon-E	1·1
Polysilicon-M2	1.1
GaAs-R	1·4

Bhar [24] had also observed a change less than 1% per 100 K for 1000 Ω-cm silicon sample.

Figures 7 and 8 show the variation of $\Delta\varepsilon'$ with temperature evaluated for some silicon samples from the temperature variation of complex dielectric permittivity. As it is not possible to evaluate the absolute value of dielectric permittivity and conductivity, the relative change in $\Delta\varepsilon'$ is calculated. Figures 7 and 8 show that $\Delta\varepsilon'$ remains constant till the sample reaches the intrinsic region and increases thereafter. The variation of $\Delta\varepsilon'$ should be similar to the variation of conductivity, but it is not observed so (see figure 9 for sample-A). In the intrinsic region, though $\Delta\varepsilon'$ increases with increase in conductivity, ε' is observed to increase with increase in temperature instead of getting decreased. Cardona *et al* [30] observed this trend and attributed

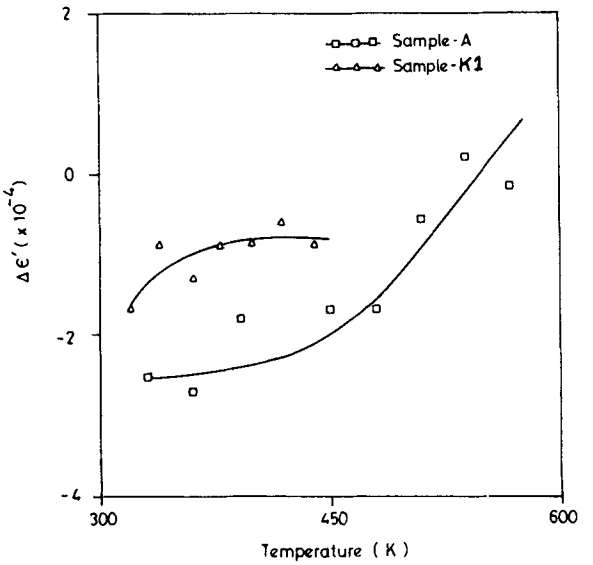

Figure 7. Variation of change in dielectric constant with temperature for samples-A and K1.

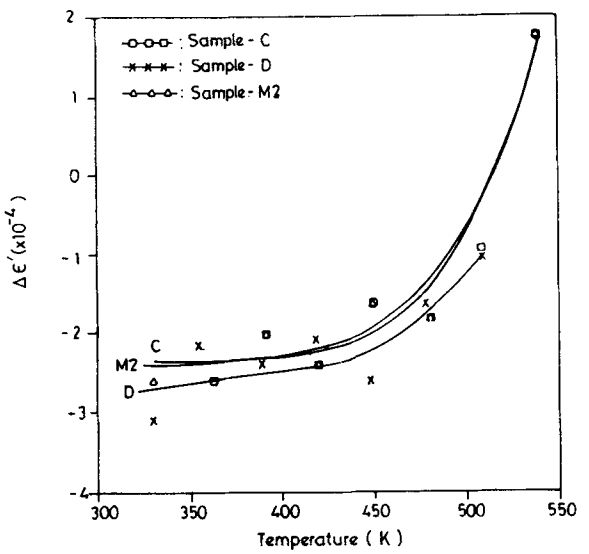

Figure 8. Variation of change in dielectric constant with temperature for samples-C, D, and M2.

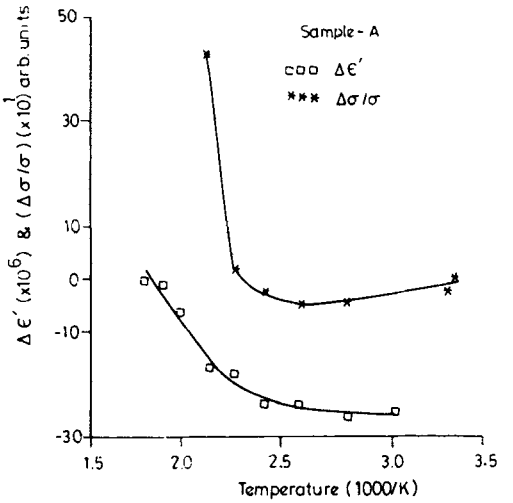

Figure 9. Variation of $\Delta\varepsilon'$ ($\times 10^6$) and ($\Delta\sigma/\sigma$) ($\times 10$) with temperature for sample-A for comparison.

to the change in the dielectric permittivity in a direction opposite to that due to carrier motion. It is also possible to suggest that the increase in ε' is the resultant of decrease in τ: The decrease of τ with increase in conductivity is the resultant of increase in the carrier concentration.

The decrease in τ may be attributed to the increase in the lattice scattering or to the electron–electron scattering or the combined effects of both. If the lattice scattering dominates over τ, then the $\Delta\varepsilon'$ should have decreased in the temperature range 300–450 K (where the conductivity reduces due to the lattice scattering), rather it remained constant. Considering the other possibility, as the carrier concentration increases, the carrier–carrier scattering increases. This decreases the momentum relaxation time. Though the electron–electron scattering is not much significant at lower concentrations of electrons, it affects the momentum relaxation time at higher concentrations (10^{16}/cm^3: in this case) [31]. For an assumed values of ε' as 12, effective mass (m^*) as 0·5 for electron, and the energy of the electron as 0·03 eV, the relation between the momentum relaxation time and carrier concentration may be given by [31],

$$\tau \propto \frac{10^4}{n} \tag{11}$$

where n is the carrier concentration expressed in cm^{-3}.

Therefore, as the carrier concentration remains constant for the temperature range 300–400 K for samples-A, C, E, and M2, $\Delta\varepsilon'$ also remains constant. But in the intrinsic region , (> 450 K), the carrier concentration increases and hence τ decreases.

Similarly, the variation of $\Delta\varepsilon'$ for sample-K1 is attributed to the increase in the carrier concentration (300–400 K) and its subsequent saturation (400–500 K). It is interesting the note that the momentum relaxation does not get affected by the variation in the conductivity but is sensitive to the carrier concentration. The

comparison between figures 4 and 6 and 7 and 8 indicates that the change in the $\Delta\varepsilon'$ indirectly gives the change in the carrier concentration.

To ensure this type of trend, instead of increasing the temperature, a 122 mW/cm^2 white light is used to increase the carrier concentration (subsequently the conductivity) of sample-A. The aim is to increase the conductivity of the sample by slowly increasing the intensity of the illumination source, thereby it is possible to study the variation of $\Delta\varepsilon'$ with conductivity. As mentioned earlier, the dielectric permittivity is directly proportional to the measurement of resonance frequency shift and the dielectric loss is proportional to the change in the quality factor. Therefore, for various intensities of the excitation source, the relative change in the permittivity is measured in terms of increase in the resonance frequency shift of the cavity. Similarly, the variation of conductivity is measured in terms of the quality factor. Figure 10 shows the cavity resonance plotted for the cavity under dark and illuminated condition loaded with sample-A showing clearly the shift in the resonance frequency due to the application of illumination intensity. It is observed that the dielectric permittivity increases with intensity and therefore with conductivity. By varying the intensity of the illumination source, the shift in the resonance frequency with the conductivity of the sample is plotted in figure 12. The change in the slope of the plot gives the relative variation of relaxation time. The decrease in τ is calculated as 3% to 87% for an increase in conductivity from 3% to 793% (σ at 300 K is 0·00286 S/cm) and $\Delta\varepsilon'$ up to 17·5%. There is not much change in $\Delta\varepsilon'$ for a change of σ up to 300%, but increase in the conductivity above this value decreases the absolute value of the ε'. This drastically reduces the relaxation time. Figure 12 shows a similar change in the resonance frequency and quality factor of the cavity loaded with sample-M2 under dark and

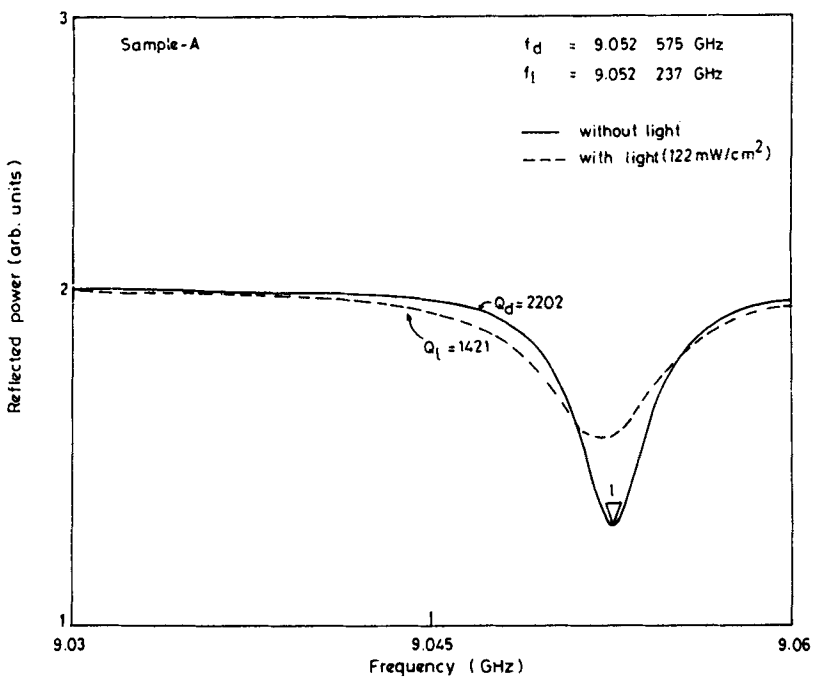

Figure 10. Cavity resonance curve for sample-A under dark and under 122 mW/cm^2 white light illumination.

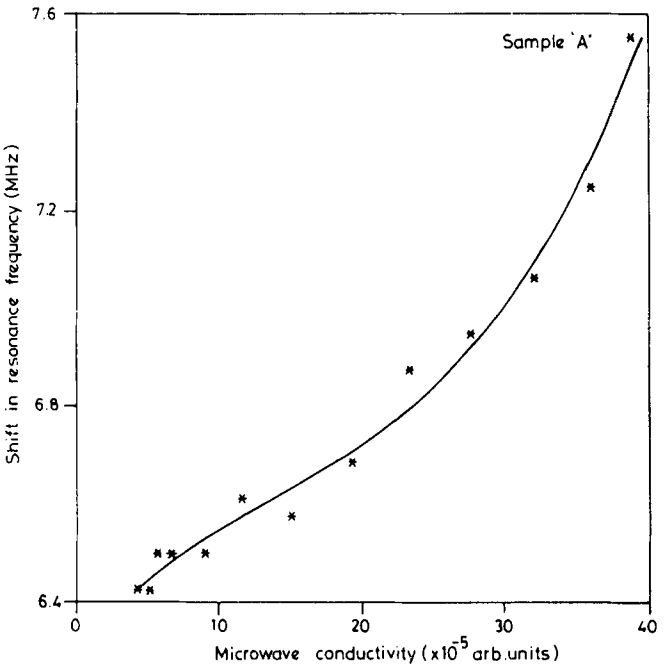

Figure 11. Shift in the resonance frequency with conductivity for sample-A.

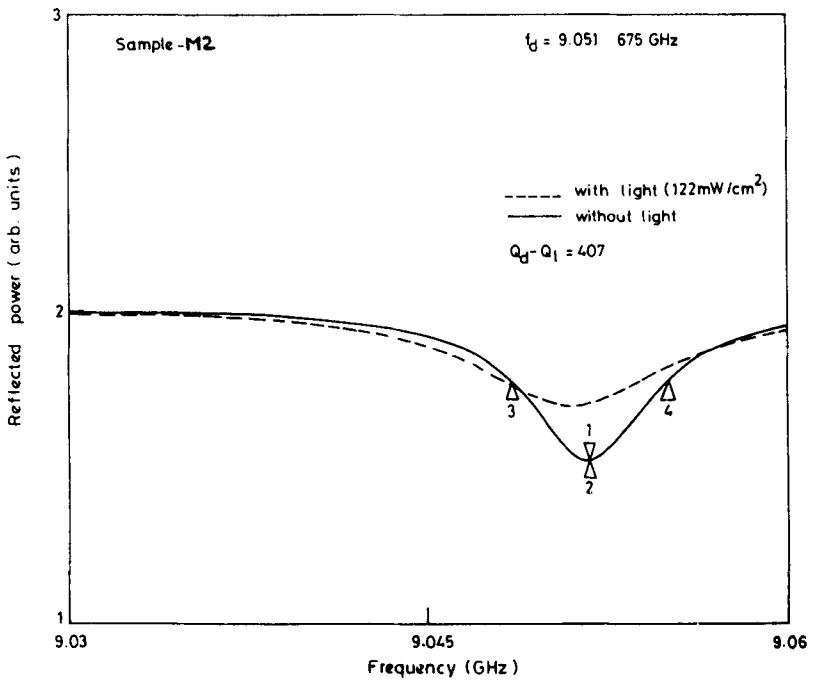

Figure 12. Cavity resonance curve for sample-M2 under dark and under 122 mW/cm^2 white light illumination.

illuminated condition. Therefore, it may be concluded that the change in $\Delta\varepsilon'$ is dominated by the change in the carrier concentration compared to the change in the conductivity.

6. Conclusion

The cavity perturbation technique is employed to observe the temperature variation of conductivity in single and polycrystalline silicon and gallium arsenide at microwave frequencies. Apart from the measurement of band gap, an attempt is made to correlate the variation of dielectric constant with the conductivity. The paper suggests that the increase of dielectric constant with increase in conductivity is due to the increase in carrier–carrier scattering resulting in the decrease of momentum relaxation time of the carriers.

Acknowledgements

One of the authors, (VS) acknowledges CSIR, New Delhi for the financial support provided through a Senior Research Fellowship. The authors wish to acknowledge INDO-US project for providing some of the experimental facilities. The authors wish to thank Mr V Sivasubramanian for useful discussions.

References

[1] H K Henisch and J Zucker, *Rev. Sci. Instrum.* **27**, 409 (1956)
[2] A P Ramsa, H Jacob, and F A Brand, *J. Appl. Phys.* **30**, 1054 (1959)
[3] C A Montgomery, in *Technique of microwave measurements*, MIT Rad. Lab. Ser., (McGraw-Hill, New York, 1947) **11**, 625
[4] G Beck and M Kunst, *Rev. Sci. Instrum.* **57**, 197 (1986)
[5] A Sanders and M Kunst, *Solid State Electron* **34**, 1007 (1991)
[6] M Kunst and A Sanders, *Semicond. Sci. Technol.* **7**, 51 (1992)
[7] K D Cummings, S J Pearton, and G P Vella-Coleiro, *J. Appl. Phys.* **60**, 1676 (1986)
[8] John M Warman, Matthijs P de Haas, Stephan W F M, van Hovell tot Westerflier, Johannes J M Binsma and Zvonimir I Kolar, *J. Phys. Chem.* **93**, 5895 (1989)
[9] B Kramer, S Gelfman and K Kalikstein, *Phys. Rev.* **B6**, 556 (1972)
[10] M C Chen, *J. Appl. Phys.* **64**, 945 (1988)
[11] S Bothra, S Tyagi, S K Ghandhi and J M Borrego, *Solid State Electron* **34**, 47 (1991)
[12] R W Fessenden, J Sobhanadri and V Subramanian, communicated to Thin Solid Films, USA
[13] S Dixon, R F Giordano and H Jacobs, *J. Appl. Phys.* **45**, 2570 (1974)
[14] S Deb and B R Nag, *J. Appl. Phys.* **33**, 1604 (1962)
[15] H Jacobs, A P Ramsa and F A Brand, *Proc. IRE* **48**, 2570 (1974)
[16] J O Artman and P E Tannenwald, *J. Appl. Phys.* **26**, 1124 (1955)
[17] K S Champlin and R R Krongard, *IRE Trans. Microwave Theory Tech.* **MTT-9**, 546 (1961)
[18] V Subramanian, B S Bellubbi and J Sobhanadri, *Rev. Sci. Instrum.* **64**, 231 (1993)
[19] V Subramanian and J Sobhanadri, *Rev. Sci. Instrum.* **65**, 453 (1994)
[20] V Subramanian, B S Bellubbi and J Sobhanadri, *Pramana – J. Phys.* **41**, 9 (1993)
[21] V R K Murthy and R Raman, *Solid State Commun.* **70**, 847 (1989)
[22] Richard W Fessenden, Paul M Carton, Henning Paul, Hiroshi Shimamori, *J. Phys. Chem.* **83**, 1676 (1979)
[23] B Lehndroff, *Meas. Sci. Technol* **3**, 822 (1992)

[24] J N Bhar, *Proc. IEEE*, **51**, 1623 (1963)
[25] F J Blatt, in *Physics of electronic conduction in solids* (McGraw Hill New York, 1968)
[26] T S Benedict and W Shockley, *Phys. Rev.* **89**, 1152 (1953)
[27] R Natarajan, D C Dube and V K Tripathi, *Indian J. Phys.* **52**, 567 (1978)
[28] H Paul Maruska, Amal K Ghosh, Albert Rose and Tom Feng, *Appl. Phys. Lett.* **36**, 381 (1980)
[29] T S Benedict, *Phys. Rev.* **91**, 1565 (1953)
[30] M Cardona, W Paul and H Brooks, in *Solid State Physics* (Academic Press, New York, 1960) vol. 1, pp. 206–214
[31] B K Ridley, in *Quantum processes in semiconductors* (Oxford University Press, New York, 1993) edn. 3, p. 175