AC conductivity of amorphous semiconductors

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Abstract. The models for dielectric relaxation which confine to well defined dielectric loss peaks suggested by the workers from dielectric school and that of frequency dependent ac conductivity suggested by the workers from semiconductor school are briefly reviewed. A brief description of the spurious effects which can give similar relaxation behaviour are also presented. Attempt has been made to explain the observed frequency and temperature dependence of ac conductivity in transition metal ion phosphate glasses by assuming two mechanisms. The first mechanism is responsible for well defined but broad dielectric loss peaks and dominates in the region where measured ac conductivity approaches dc conductivity. Such a mechanism can give a slope of 0.5 over several decades of frequency even in the region where measured ac conductivity is substantially higher than dc conductivity. The second mechanism is responsible for almost linear or sublinear frequency dependent ac conductivity and dominates in the temperature and frequency region where measured ac conductivity is substantially higher than dc conductivity. Measurements of dielectric constant in other amorphous systems in the region where measured ac conductivity approaches dc conductivity are needed to check the validity of the model and the exact origin of the two mechanisms of ac conductivity.

Keywords. Dielectrics; amorphous semiconductors; dielectric relaxation; ac conductivity.

1. Introduction

Electrical properties of glasses (amorphous material) have always been of interest. There has been renewed interest in soda silicate and similar other oxide glasses which are usually insulators having ionic conduction. Recently interest has shifted to the semiconducting glasses and amorphous films because of their potential application in electronic devices. This class includes chalcogenide glasses and glasses containing transition metal oxides as well as amorphous thin films of silicon, germanium, selenium, tellurium and many other insulator materials all of which are mainly electronic conductors.

In this talk, the low frequency ac characteristics of electronic conducting glasses and amorphous thin films will be briefly reviewed with special emphasis

on glasses containing transition metal oxides. A short description of the basic theories of dielectric relaxation and other spurious effects which can give similar relaxation effect are first presented. This is followed by experimental observations and various interpretations. Finally the most plausible explanations are presented. The difference in the approaches of the workers from dielectric school and semiconductor school is pointed out.

2. Basic theory

2.1. Dielectric loss and ac conductivity

If a periodic field E is impressed on a dielectric material (which has no free charges) the polarization charge will vary in the periodic manner but its phase will lag slightly behind that of applied electric field. The material can be characterized by a complex dielectric constant ϵ^*

$$\epsilon^* = \epsilon' - j\epsilon'', \quad (1)$$

where ϵ' is the dielectric constant and ϵ'' the dielectric loss. It can be shown (Kubo and Nagamiya 1969) that the energy loss L in the system is given by

$$L = \omega \epsilon_0 \epsilon'' (A/t) E^2, \quad (2)$$

where A is the area and t is the thickness of the sample and ϵ_0 is the free space permittivity. In analogy with dc conductivity we can immediately identify $\omega \epsilon_0 \epsilon''$ as the conductivity of the sample under ac fields and define ac conductivity as

$$\sigma(\omega) = \omega \epsilon_0 \epsilon''. \quad (3)$$

It may be emphasised that ac conductivity has been defined as the losses due to bound charges and as such there should be no losses under a dc electric field. However, every material will have some free charges and under the applied low frequency or even at microwave frequencies these charges can follow the field and cause conduction current giving rise to energy loss. At dc fields we will have the contribution of only free charges and at ac fields the energy loss will be both due to free and bound charges. The measured ac conductivity $\sigma_m(\omega)$ is thus given by

$$\sigma_m(\omega) = \sigma_{dc} + \sigma(\omega). \quad (4)$$

It is customary among workers of dielectric school to characterize the system by its dielectric constant ϵ' and loss ϵ'' , while those from semiconductor school characterize a system by its conductivity.

2.2. Dielectric polarization

When we discuss ac conductivity or dielectric constant of a system we are mainly concerned with the response of electric polarization as a function of frequency. The total polarisation in a dielectric material consists of electronic, ionic (or atomic) and dipolar contributions. In materials with permanent dipoles the

contribution due to dipolar polarization dominates at low frequencies (figure 1a). The dipolar polarization was first observed in polar liquids having permanent electric dipole moment due to asymmetry of molecules and the formal theory for dielectric dispersion in liquids was first proposed by Debye (1929). The dielectric dispersion due to permanent dipoles in liquids has been observed at low frequencies as well as at microwave frequencies but not beyond (Hill *et al* 1969). However, most of these polar liquids on freezing show no contribution of dipole polarization and the static dielectric constant falls to a low value on freezing (Krishnaji and Mansingh 1966) (figure 1b).

The concept of permanent dipoles of liquids cannot be directly applied to solids which show a dispersion at low or microwave frequencies. The temperature dependence of dielectric constant in these solids is also similar to that of polar liquids. The polarization analogous to dipole polarization in solids was explained by Frohlich (1958) assuming a bipotential model (figure 1c). Let an ion or electron has two equilibrium positions separated by a distance b and the potential barrier between them is V . In the absence of electric field the electron will spend equal time in both the wells. However, in the presence of an external field E a distortion in the potential wells is caused and the probability of spending more time in one of the wells increases, giving rise to effective (Frohlich 1958) moment

$$\left(\frac{1}{2}eb\right)^2 \frac{\cos^2 \theta E}{kT} + e\bar{r}. \quad (5)$$

This polarization, although caused in the presence of an electric field, behaves in terms of its temperature dependence as a permanent dipole of moment $eb/2$. Thus in solids where the charge carriers (electrons or ions) are localized and the conduction is by hopping from one localized state to the other, one can get a dipolar polarization and a dispersion at low frequencies just as in polar liquids. It may be emphasised (Frohlich 1958) that the low frequency saturation dielectric constant

Figure 1. (a) A schematic representation for the frequency dependence of several contributions to the polarizability. (b). Variation of dielectric constant with temperature for nitrochloroform. (c). Potential energy of a charge centre with two equilibrium positions separated by a distance b , in the absence of electric field (—) and under an applied electric field E (···).

for a dipolar system is expected to be inversely proportional to temperature, while for a nonpolar (only ionic and electronic polarization) the dielectric constant is expected to show little dependence on temperature.

2.3. Dielectric dispersion

The response of dielectric polarization (complex dielectric constant ϵ^*) in the presence of sinusoidal field can be expressed in terms of a decay function $\phi(t)$ in the following (Kubo and Nagamiya 1969) form

$$\epsilon^* = \epsilon_\infty + \int_0^\infty \phi(t) \exp(j\omega t) dt, \quad (6)$$

where ϵ_∞ represents that part of polarization which immediately follows the field, and for systems in which we are interested in the decay of dipolar polarization, ϵ_∞ represents the contribution of ionic and electronic polarizations. For a well-defined single relaxation time τ

$$\phi(t) = \frac{(\epsilon_0 - \epsilon_\infty)}{\tau} \exp(-t/\tau), \quad (7)$$

and substitution of (7) in (6) and separating real and imaginary parts gives the famous Debye relations (Frohlich 1958)

$$\epsilon'(\omega) - \epsilon_\infty = (\epsilon_0 - \epsilon_\infty)/(1 + \omega^2 \tau^2), \quad (8a)$$

$$\epsilon'' = (\epsilon_0 - \epsilon_\infty) \omega \tau / (1 + \omega^2 \tau^2), \quad (8b)$$

where ϵ_0 represents the static dielectric constant or the dielectric constant at frequencies where the dipoles can follow the field. The relations similar to (8) were first given by Debye for polar liquids using a different approach in which rotation of rigid dipole sphere in a viscous liquid was considered.

2.4. Distribution of relaxation times

It has been observed that Debye-type relaxation with a single relaxation time is seldom observed and usually there is a distribution of relaxation times. One may either introduce a finite number of relaxation times τ_i or assume that the relaxation time has a continuous distribution. In the latter case, if we assume that $\phi(t)$ is given by (Hill *et al* 1969)

$$\phi(t) = \int_0^\infty \exp(-t/\tau) \frac{g(\tau)}{\tau} d\tau, \quad (9)$$

then on substituting (9) in (6) we get

$$\epsilon'(\omega) - \epsilon_\infty = \int_0^\infty \frac{g(\tau)}{1 + \omega^2 \tau^2} d\tau, \quad (10a)$$

$$\sigma(\omega) = \omega \epsilon_0 \epsilon''(\omega) = \int_0^\infty \frac{\epsilon_0 g(\tau) \omega^2 \tau}{1 + \omega^2 \tau^2} d\tau. \quad (10b)$$

In explaining the dielectric constant and ac conductivity of a system we are interested in finding the proper distribution function $g(\tau)$.

Several distribution functions have been suggested (Hill *et al* 1969; Frohlich 1958; McCrum *et al* 1967). However, the effect of distribution of relaxation times on the dielectric constant and $\sigma(\omega)$ can be conveniently demonstrated by an empirical distribution due to Cole and Cole. They suggested an empirical modification of Debye relations (8) and gave the complex dielectric constant as

$$\epsilon^*(\omega) = \frac{\epsilon_0 - \epsilon_\infty}{1 + (i\omega\tau)^{1-a}}, \quad (11)$$

where a is an empirical distribution parameter lying between 0 and 1. $a = 0$ corresponds to a single relaxation time which reduces equation (11) to (8), while a close to 1 corresponds to an infinite distribution of relaxation time. Separating, real and imaginary parts one gets

$$\epsilon'(\omega) - \epsilon_\infty = \frac{(\epsilon_0 - \epsilon_\infty) [1 + (f/f_0)^{1-a} \sin(a\pi/2)]}{1 + 2(f/f_0)^{1-a} \sin(a\pi/2) + (f/f_0)^{2(1-a)}}, \quad (12a)$$

$$\sigma(\omega) = \frac{\omega\epsilon_0(\epsilon_0 - \epsilon_\infty) [1 + (f/f_0)^{1-a} \cos(a\pi/2)]}{1 + 2(f/f_0)^{1-a} \sin(a\pi/2) + (f/f_0)^{2(1-a)}}. \quad (12b)$$

A plot of $\epsilon'(\omega)$, $\epsilon''(\omega)$ and $\sigma(\omega)$ for values of $a = 0, 0.5$, and 0.9 is given in figures 2a, b, c respectively. The value of $(\epsilon_0 - \epsilon_\infty)$ has been assumed equal to 10 and the relaxation frequency $f_0 = 1/2\pi\tau$ has been assumed equal to 10^3 Hz. It may be noticed that for (i) a well-defined single relaxation time $a = 0$, $\sigma(\omega)$ shows a quadratic dependence on frequency f below f_0 and is frequency-independent above f_0 . The dielectric constant falls rapidly near the relaxation frequency and within 1.4 decade changes from ϵ_0 to ϵ_∞ . (ii) For a finite distribution of relaxation times $a = 0.5$ we notice that the slope of $\log \sigma(\omega)$ vs $\log \omega$ below f_0 is 1.5 while it is 0.5 for several decades above f_0 . The dielectric constant shows a less rapid change with frequency. A peak in ϵ'' can also be clearly noticed. (iii) For $a = 0.9$ which corresponds to a very wide distribution of relaxation times, the slope of $\log \sigma(\omega)$ vs $\log \omega$ is 0.9, and the change of slope at f_0 is hardly noticeable. The dielectric constant is a slowly decreasing function of frequency and there is hardly any peak in ϵ'' .

We can thus conclude that for (a) a narrower distribution of relaxation times, the slope above f_0 is much less than unity but greater than zero. The dielectric loss peaks are broad but well-defined, (b) a wide distribution of relaxation times the conductivity is almost linearly dependent on frequency and dielectric constant slowly decreases with the frequency, a well-defined average dielectric relaxation time and a peak in ϵ'' loses its significance.

2.5. Difference in dielectric and semiconductor schools

The workers from dielectric school were always interested in looking at the peaks in ϵ'' (narrow distribution of relaxation times) and interpreting the results close to these loss peaks. They did not interpret the results in the frequency regions far removed from loss peaks or the materials which had a finite frequency-independent or slightly frequency-dependent dielectric loss but no well-defined

Figure 2. Variation of (a) dielectric constant, (b) dielectric loss, (c) ac conductivity with frequency for a Debye-type dispersion with single relaxation time (---), with a narrow distribution of relaxation time $\alpha = 0.5$ (—), and for a wide distribution of relaxation times, $\alpha = 0.9$ (- · - ·).

loss peaks. A frequency-independent ϵ'' implies a linear dependence of $\sigma(\omega)$ on ω according to equation (3). This was experimentally observed in many solids (Von Hippel 1954) by workers from dielectric school but no importance was given to this observation (Hollander and Castro 1962).

Contrary to this, workers from the semiconductor school have shown more interest in the region where measured ac conductivity is substantially higher than dc conductivity and shows a linear or sublinear frequency dependence (wide distribution of relaxation times) (Mott and Davis 1979). This phenomenon was interesting to them because normally in band semiconductors the measured ac conductivity is equal to dc conductivity upto about microwave frequencies, while a frequency-dependent conductivity is an indication of hopping between localized states (bipotential model).

We shall call the first type of studies conducted by the workers from dielectric school as "Dielectric relaxation studies" and the second type of studies conducted by workers from the semiconductor school as "AC conductivity studies".

3. Dielectric relaxation

Extensive studies have been made in polar liquids and polymers (Hill *et al* 1969; McCrum *et al* 1967) in which usually the d.c. conductivity is almost negligible. Attempts have been made to explain the experimental data by suitable symmetric and asymmetric distribution functions and to associate *qualitatively* the distribution of relaxation times with the overall and group rotation of the molecules. Smyth (1966) pointed out that *quantitative* analysis, in terms of two or three well-defined relaxation times, usually ends up in making an educated guess about their physical significance.

The studies in solids have shown the existence of well-defined dielectric loss peaks in ionic conducting glasses (Charles 1961; Taylor 1959), transition metal ion glasses (Mansingh *et al* 1975a; Rawal and MacCrone 1978; Anderson and MacCrone 1974), concentrated aqueous solutions (Moynihan *et al* 1971), fused salts (Macedo and Weiler 1969), oxide ceramics (Razilowskii *et al* 1969) as well as single crystals of alkali halides (Kao *et al* 1970) and some transition metal oxides (Bosman and Van Daal 1970; Mansingh *et al* 1978a). The main feature of the dielectric relaxation in solids is that the loss peaks are broad and the distribution parameter is independent of temperature. The activation energies from the temperature dependence of dielectric relaxation frequencies [$f_0 \propto \exp(\Delta E_D/kT)$] and dc conductivity [$\sigma_{ac} \propto \exp(\Delta E_{ac}/kT)$] in most of the cases is almost equal. A close correlation between the dc conductivity and dielectric relaxation has been noted in amorphous (Koichi *et al* 1978) As_2Se_3 undoped and doped with silver. These measurements were made by absorption current and the results predict a Debye-type loss peaks with a single relaxation time. Panwar *et al* (1980) have measured powdered pellets of some chalcogenide glass and observed a decrease in the distribution parameter with increasing temperature.

The theoretical models which have been proposed to explain the dielectric relaxation in amorphous solids can be classified into two groups; (i) spurious phenomena, (ii) bulk phenomena and are described in the following section.

3.1. Spurious phenomena

A dispersion similar to the Debye dispersion in which the activation energies for dielectric relaxation and dc conductivities are expected to be equal can be given by the following two reasons.

3.1a. *Electrode barrier* : In the presence of surface barriers at the electrodes, the electrical equivalent of the sample can be given as shown in figure 3. The capacitances C_1 and C_2 represent the surface and bulk capacitance and R_1 and R_2 the resistances of the surface and bulk. The dielectric constant ϵ' and conductivity $\sigma(\omega)$ is evaluated from the equivalent parallel impedance of the sample as shown in figure (3b). If we assume that C_1 , R_1 and C_2 , R_2 are independent of frequency then the equivalent C_p and R_p are given by (Mansingh *et al* (1979)

$$C_p = \frac{C_1 R_1^2 (1 + \omega^2 C_2^2 R_2^2) + C_2 R_2^2 (1 + \omega^2 C_1^2 R_1^2)}{R_1^2 (1 + \omega^2 C_2^2 R_2^2) + R_2^2 (1 + \omega^2 C_1^2 R_1^2) + 2R_1 R_2 (1 + \omega^2 C_1 C_2 R_1 R_2)}, \quad (13a)$$

$$R_p = \frac{R_1^2 (1 + \omega^2 C_2^2 R_2^2) + R_2^2 (1 + \omega^2 C_1^2 R_1^2) + 2R_1 R_2 (1 + \omega^2 C_1 C_2 R_1 R_2)}{R_1 (1 + \omega^2 C_2^2 R_2^2) + R_2 (1 + \omega^2 C_1^2 R_1^2)} \quad (13b)$$

If we assume that $C_1 \gg C_2$ and $R_1 \gg R_2$ then it can be shown that if $\omega C_1 R_2 \ll 1$, then $C_p = C_1$ and $R_p = R_1$, and if $\omega C_1 R_2 \gg 1$, then $C_p = C_2$ and $R_p = R_2$. The dispersion frequency is controlled by barrier capacitance and bulk resistance, and is expected to be important in low resistance samples or films.

The variation of C_p and R_p as a function of frequency can be easily calculated from (13a) and (13b) and it can be shown that the behaviour is exactly similar to that for a Debye-type relaxation with a single relaxation time. This is a very simplified assumption of barrier model, and a complex dependence of C_p on ω is expected if the relaxation time of surface states and their distribution is also taken into account (Sze 1979).

The problem of ohmic contacts in transition metal ion phosphate glasses has been discussed by Sayer and Mansingh (1979). Figure 4 gives a sample curve of I-V, $C_p - f$ and $G_p - f$ for a glass with good and bad electrodes. It may be noted that the conductivity is showing almost a square law dependence for a bad contact. We have noticed that if measurements are made as a function of tempe-

Figure 3. A simple barrier-model. The barrier capacitances and resistances at the two electrodes have been assumed identical and replaced by a single capacitance and resistance C_1 and R_1 respectively. C_2 and R_2 represent the bulk capacitance and resistance. The measured equivalent capacitance and resistance are C_p and R_p respectively from which dielectric constant and loss are evaluated.

Figure 4. V - I plots, and the frequency dependence of parallel capacitance and conductivity for samples of $\text{WO}_3 : \text{P}_2\text{O}_5 : 1.3\% \text{V}_2\text{O}_5$ possessing "good" contacts —●— and "bad" contacts —○— $T = 225 \text{ K}$.

ratures and fixed frequencies, then the dielectric constant variation with temperature is a more sensitive indication of surface barriers than conductivity. The variation of ϵ' vs T is shown in figure 5 for good and bad contacts (Mansingh *et al* 1980b). In samples with bad electrodes the dielectric constant keeps on increasing with temperature, while with good electrodes it saturates to a reasonable value. To ensure that the measured values represent the bulk values measurements should be made on different thicknesses of the sample. If the surface barrier or electrode polarization effects dominate the values of C_p and R_p will be independent of thickness and the corresponding dielectric constant and conductivity will be thickness-dependent. Usually the barrier capacitance is very large as compared to bulk, and so the numerical values of dielectric constant are also a good indication of the presence of barriers on a single thickness sample.

3.1b. *Inhomogeneities*: The dielectric dispersion due to the presence of materials of different conductivities is usually termed as Maxwell-Wagner polarization. In a simplified model the inhomogeneity can be considered as two layers of different dielectric constants and conductivities placed on each other. The

Figure 5. Variation of dielectric constant with temperature at fixed frequencies for good and bad electrodes in a Ti-doped VO_2 crystal.

electrical equivalent will be similar to that shown in figure 3 and a Debye-type dispersion can thus be envisaged.

The inhomogeneities are randomly distributed in the sample and cannot be detected by measurements on samples of different thicknesses. In general, it is very difficult to ascertain whether the low frequency dispersion is due to bulk or inhomogeneities by dielectric measurements alone. Israd (1962) interpreted the dielectric dispersion in oxide glasses by the Maxwell-Wagner model. However, in some cases measurements of low frequency saturation or static dielectric constant can give an indication whether the low frequency dispersion is due to inhomogeneities or a bulk phenomenon. The static dielectric constant for a simple two layer model can be given by (Kamiyoshi *et al* 1967)

$$\epsilon_0 = \frac{\epsilon_1 \epsilon_2}{u_1 \epsilon_2 + u_2 \epsilon_1} + \frac{(\epsilon_2 \sigma_1 - \epsilon_1 \sigma_2)^2 u_1 u_2}{(\epsilon_1 u_2 + \epsilon_2 u_1)(\sigma_1 u_2 + \sigma_2 u_1)^2}, \quad (14)$$

and
$$\epsilon_\infty = \frac{\epsilon_1 \epsilon_2}{u_1 \epsilon_2 + u_2 \epsilon_1}$$

where ϵ_1 , ϵ_2 and σ_1 , σ_2 are the dielectric constant and conductivity of two media of thickness fraction u_1 and u_2 respectively. If the inhomogeneity is the presence of an insulating medium ($\sigma_2 \rightarrow 0$), in bulk medium 1 or a conducting medium ($\sigma_2 \rightarrow \infty$) then ϵ_0 according to (14) is expected to be independent of temperature. However, in other cases the temperature dependence of ϵ_0 will come from the

temperature dependence of σ_1 and σ_2 as ϵ_1 and ϵ_2 are expected to be independent of temperature. Leaving some special cases, ϵ_0 will not be inversely proportional to temperature T as predicted for bulk phenomenon. The limiting high temperature ($T \rightarrow \infty$) value of ϵ_0 is also not predicted equal to limiting high frequency value ϵ_∞ from (14) while for bulk phenomena one expects the value of ϵ for $T \rightarrow \infty$ should be equal to ϵ_∞ .

3.2. Bulk phenomenon

The models which predict a Debye-type dispersion due to bulk effect and a close correlation between the activation energies for dielectric relaxation and dc conductivity have been suggested by different workers (Charles 1961; Taylor 1959; Rawal and MacCrone 1978; Stevels 1957; Mansingh *et al* 1978b; Doe 1978; Nakajima 1972) and can be broadly classified into following groups:

3.2a. *Random potential well model*: Stevels (1957) and Taylor (1959) proposed models which basically assume that there are potential energy barriers of various heights. It has been suggested that for dc conduction the highest energy barrier has to be overcome while for ac conduction the migration across the limited distance overcoming the lower energy barrier is required. These models predict the dc activation energy to be slightly higher than activation energy for dielectric relaxation. Mansingh *et al* (1978b) suggested linear chains of different potential wells to account for the same activation energy for dc conductivity and dielectric relaxation.

3.2b. *Conducting path model*: Charles (1961) suggested that specific path of charge carriers can give rise both to dielectric polarization and dc conduction. A more detailed analysis has been presented by Nakajima (1972). In this model, he assumed that there are only two stable sites adjacent to each site and that the movement of charge carriers is restricted to a zig zag path turning at random directions. Under an applied field, probabilities of a charge carrier making a transition will differ from site to site because of different angles between each jump direction and the applied field. Therefore, the polarization current due to charge accumulation will be included in conduction current. Considering a regular zig zag path he has shown that the dielectric relaxation strength ($\epsilon_0 - \epsilon_\infty$), dielectric relaxation frequency and dc conductivity can be correlated by the following equation

$$\sigma_{dc} = 2\pi \epsilon_0 (\epsilon_0 - \epsilon_\infty) f_0. \quad (15)$$

This relationship is found to hold in a variety of ionic conducting oxide glasses (Nakajima 1972).

4. AC conductivity

A Debye-type loss due to thermally activated hopping was first observed by Pollak and Gebelle (1961) in n-type silicon. They observed that at low temperature the ac conductivity is considerably higher than dc conductivity and increases

with increasing frequency, such that $\sigma(\omega)$ can be represented by the following relation

$$\sigma(\omega) = A\omega \quad (16)$$

where s is close to 0.8 and the parameter A shows little dependence on temperature. This was attributed to the hopping of electron within the impurity band between occupied and unoccupied donor sites (impurity conduction). In the last ten years a frequency-dependent conductivity similar to the (16) has been observed in several semiconducting glasses and amorphous thin films, and is associated with electronic hopping conduction. However, such a behaviour is not limited to amorphous semiconductors as it has been found to be present in several low mobility or dielectric crystalline materials (§ 2.5). Its association with electronic hopping has been questioned by Fritzsche (1974) and Jonscher (1975). Such a behaviour can be due to spurious effects, but if it is a bulk phenomenon, then it is predicted for the bipotential model discussed in § 2.2, while the hopping can be due to either electrons or atoms, (Pollak and Pike 1972) (provided a net motion charge occurs). Recent experimental studies by Webb *et al* (1978) have shown that at low temperatures where a frequency-dependent conductivity is observed in an ionic conductor β -AgI, the major contribution is from electronic hopping.

Even in the amorphous semiconductors in which evidences other than that of ac conductivity suggest electronic hopping conduction, experimental results show a wide variation in the numerical value of s and its temperature dependence, between different systems and the same system reported by different authors. On the basis of reported results one can find that the parameter s is:

- (i) Less than unity close to 0.8 (Pollak and Gebelle 1961; Mott and Davis 1979),
- (ii) Anywhere between 0.5 to 1 (Jonscher 1972),
- (iii) Greater than unity (Kucka and Kristofik 1978; Gilbert and Adkins 1976)
- (iv) Greater than unity only at frequencies greater than 10^6 Hz (Owen and Robertson 1970; Linsley *et al* 1970; Kitao *et al* 1976),
- (v) Decreases with increasing temperature (Lakatos and Abkowitz 1971; Sayer and Mansingh 1972),
- (vi) Increases with increasing temperature (Narasimhan *et al* 1976),
- (vii) Independent of temperature (Arizumi *et al* 1974).

Most of the studies report only $\sigma(\omega)$ and do not report $\epsilon'(\omega)$. It has already been pointed out in § 3 that the measurement of $\epsilon'(\omega)$, especially the low frequency saturation value ϵ_0 , as a function of sample thickness and temperature is very important in determining whether the measured dispersion is due to spurious or bulk effect. Unfortunately, these measurements are lacking in majority of cases. The models for spurious phenomenon discussed in § 3 can be extended by taking a combination of several capacitances and resistances to get any desired frequency dependence over a few decades of frequency range. The resistance of electrode material and contact resistances also become very important at high frequencies in giving a superlinear frequency dependent conductivity (Lakatos and Abkowitz 1971). However, we will discuss the models which consider frequency-dependent $\sigma(\omega)$ as a bulk phenomenon.

The models for superlinear frequency dependence at high frequencies have been presented by Pollak (1971, 1976), Austin and Garbett (1971), and Elliot (1978). Pollak has shown that ω^2 dependence at high frequencies cannot be due to direct photon absorption. He has suggested that ω^2 dependence can be due to the cut-off in transition rates of hopping or it can be caused by correlation effects. Austin and Garbett (1971) suggest quite a different mechanism for the high frequency conductivity (above 1 MHz). In their model it arises from a long low energy tail to phonon absorption processes. Elliot (1978) showed that a superlinear frequency dependence can be a consequence of particular spatial probability distribution for charged centres in chalcogenide glasses, while the fundamental mechanism is the simultaneous hopping of two electrons over the barrier separating two oppositely charged centres.

The models which have been developed to account for the sublinear frequency-dependent conductivity can be classified as (a) quantum mechanical tunnelling models (Pollak and Gebelle 1961; Pollak 1971, 1976; Austin and Mott 1969) (QMT) where the electron hopping from one site to another is considered to be due to hopping through the barrier, and (b) the others which predict slopes closer to unity and a decrease with increasing temperature are due to Pike (1972) and Elliot (1977, 1978) who consider hopping over the barrier and hopping over the barrier models (HOB). Butcher and Morys (1973) presented a more general analysis of Debye-type hopping conduction which can be applied to both QMT and HOB as well as to hybrid cases.

The models based on QMT and HOB have been extensively used in interpreting the ac data, of amorphous semiconductors hence in the following section we will examine these models.

4.1. Quantum mechanical tunnelling

The model for frequency dependent conductivity similar to the experimentally observed behaviour of (16) was first proposed by Pollak and Gabelle (1961). They assume that conduction in doped and compensated semiconductors arises from tunnelling between neighbouring donor impurity states, randomly situated in space and energy. A theory formulated on this basis, results in the following expression for ac conductivity (Mansingh *et al* 1975b) (valid between 100 Hz and 100 kHz)

$$\sigma(\omega) = \frac{\pi}{123} |s/2| \overline{|1-s/2|} (\omega\tau)^s \tau^{-1} \frac{N^2 e^2}{kT} (11 a)^5. \quad (17)$$

It is apparent from (17) that $\sigma(\omega)$ is almost independent of temperature, which was in conflict with the observed behaviour. Pollak (1965) suggested that the temperature dependence of conductivity is due to multiple hops, however, even if three or four hops are considered the temperature dependence of conductivity remains weak (Mansingh *et al* 1975b). Kabashima *et al* (1972) observed a strongly temperature-dependent conductivity in VO_2 , and suggest that the temperature-dependent conductivity is due to neglect of disorder energy term. However, their expression suggests that strong temperature dependence in $\sigma(\omega)$ should start at the same temperature for all frequencies. Experimental results (Sayer *et al* 1971) (figure 6) show that strong temperature dependence starts at higher tempe-

Figure 6. Semilog plot of the real part of the ac conductivity *versus* $1000/T$ for the argon treated V_2O_5 - P_2O_5 glass.

rature for higher frequencies. It appears from equation (16) that any value of s can be accepted in (17). However, the assumptions made in deriving the equation result in unrealistically high values for ν_{ph} (characteristic phonon frequency) for values of s approaching unity (Pike 1972).

Hopping conduction by electrons with energies near the Fermi level, provided $N(E_F)$ is finite, have been considered by several workers. Assuming that hopping is between independent pairs of centres (multiple hopping can be neglected) and it is uncorrelated (i.e., there is no correlation between the hop distance and hop energy). Pollak (1971) has derived the following expression:

$$\sigma(\omega) = \frac{\pi^3}{96} e^2 kT \{N(E_F)\}^2 a^{-5} \omega \left[\ln \left(\frac{\nu_{ph}}{\omega} \right) \right]^4. \quad (18)$$

Austin and Mott (1969) obtained a factor $\pi/3$ and Butcher and Hayden (1977) a factor $3.66 \pi^2/6$ instead of $\pi^3/96$; except for this difference their expressions are same as (18).

Assuming $\nu_{ph} = 10^{13}$ Hz, expression (18) suggests a slope of 0.8 in the frequency region 10^2 to 10^6 Hz. The slope is independent of temperature and $\sigma(\omega)$ shows a linear dependence on temperature. Equation (18) has been used by several

workers to estimate the density of states $N(E_F)$ near the Fermi level, Abkowitz *et al* (1976) compared the value of $N(E_F)$ obtained from expression (18) and from an analysis of dc conductivity data for variable range hopping, for amorphous Ge. The values from (18) are about two orders of magnitude higher and come in the range of 10^{20} – 10^{22} , which suggests an extended rather than localized states. The inadequacy of (18) in deriving $N(E_F)$ has also been discussed by Fritzsche (1974). The variation of slope s with frequency according to (18) is given by

$$s = 1 - \frac{4}{\ln(v_{ph}/\omega)}. \quad (19)$$

The value of s in a given frequency region can be adjusted by choosing proper value of v_{ph} . At a particular frequency, say $\omega = 10^4 \text{ sec}^{-1}$, s varies from 0.4 to 0.8 for v_{ph} in the range 10^7 – 10^{13} Hz. However, the range of frequency for which a constant slope will be observed will be limited to lower values of ω for lower values of v_{ph} . Hence a slope of 0.4 or 0.5 over several decades of frequency observed in some materials cannot be accounted by adjusting v_{ph} (Kabashima *et al* 1972; Reyes *et al* 1976; Sayer *et al* 1975).

The temperature variation of slope in (18) can be brought about by assuming that v_{ph} varies in case of polarons according to $v_{ph} = v_0 \exp(-W_p/KT)$, where v_0 is the frequency of undistorted lattice and W_p the polaron binding energy. The resulting temperature variation of s is given by

$$\frac{ds}{dT} = \frac{4W_p}{2KT^2} \cdot \frac{1}{\{\ln v_0/\omega - (W_p/2KT)\}^2} \quad (20)$$

Equation (20) predicts an increase of s with increasing temperature. Instances of such a positive coefficient of s have been reported (Narasimhan *et al* 1976) for evaporated films of Ge and InSb in which the possibility of polaron formation from other evidences are unlikely. However, in vanadate glasses (Sayer *et al* 1971), which show a strong possibility of polaron formation, give a decrease of s with increasing temperature.

The QMT models give a value of s which is close to 0.8, and does not predict a decrease of slope with increasing temperature. For the value of s in excess of 0.8 equation (19) suggests unreasonably high values of $v_{ph} = 10^{39}$ (e.g. $s = 0.96$ and $\omega = 10^4 \text{ sec}^{-1}$). A smaller slope cannot be predicted for several decades of frequencies. The model also fails to give any low frequency limit.

4.2. Hopping over the barrier model

Pike (1972) suggested a model in which instead of QMT, the hopping was considered to be over the barrier W , within the localized band while excitation to conduction band having a barrier W_M , gives rise to dc conduction and well-defined dielectric loss peaks with ω^2 frequency dependence. The distribution in relaxation times comes due to the distribution in barrier heights which is correlated to the jump distances. Assuming the hopping between adjacent pairs, which are randomly distributed with different barrier heights, the following expression is obtained for ac conductivity (Elliot 1977, 1978)

$$\sigma(\omega) = \frac{\pi^2 N^2 \epsilon}{24} \left(\frac{8e^2}{k W_M} \right)^6 \frac{\omega^8}{\tau_0^6}, \quad (21)$$

$$\text{where } \beta = 1 - s = \frac{6kT}{W_M}, \quad (22)$$

$$\tau_{\max} = \tau_0 \exp (W_M/kT), \quad (23)$$

where $\tau_{\max}$ is the relaxation time corresponding to well-defined dielectric loss peak, and W_M is the activation energy for dielectric loss peaks. The equation (21) is valid for frequencies $\omega > 1/\tau_{\max}$. Equation (22) gives a correlation between the barrier heights W_M and the exponent s . Elliot has shown that there is a good agreement between predicted s from (22) and experimentally observed values in chalcogenide glasses. Equation (22) predicts a decrease in s with increasing temperature. The calculated values of N from (21) also appear quite reasonable for chalcogenide glasses.

The HOB model does predict a low frequency limit and decreases of s with temperature. However, the model gives a temperature dependence of $\sigma(\omega)$ which is not consistent with the observed behaviour in vanadate glasses (Mansingh *et al* 1975b). Even in chalcogenide glasses the temperature dependence cannot be adequately explained. For example (Lakatos and Abkowitz 1971) in As_2Se_3 , the conductivity at 1 kHz increases from $3 \times 10^{-12} \Omega^{-1} \text{cm}^{-1}$ to $5 \times 10^{-12} \Omega^{-1} \text{cm}^{-1}$ when the temperature is changed from 153 K to 250 K while between 250 and 300 K, the conductivity changes from $5 \times 10^{-12} \Omega^{-1} \text{cm}^{-1}$ to $1 \times 10^{-11} \Omega^{-1} \text{cm}^{-1}$. Apart from the temperature variation of $\sigma(\omega)$, this model becomes unacceptable for the materials which show a slope s of 0.8 at 77 K as it predicts a change in the value of s from 0.8 to 0.4 when the temperature is raised to 300 K. A value of $s = 0.98$ changes to 0.922 in this temperature range. The measured $\sigma_m(\omega)$ at different frequencies and fixed temperatures is shown in figures 7 and 8 for $\text{WO}_3 - \text{P}_2\text{O}_5$ glass (Mansingh *et al* 1980 a). it may be noted that the slope in the frequency region 10^7 to 10^9 at 300 K is not less than the slope at 77 K in the frequency region 10^2 to 10^5 Hz. While at 168 K, the slope is close to 0.5 between 10^4 and 10^5 Hz even after taking out the contribution of dc conductivity.

Figure 7. Measured conductivity of 67/33 tungsten phosphate glass at four fixed temperatures as a function of frequency.

Figure 8. Total measured conductivity plotted as a function of frequency at room temperature for the three glass systems.

This shows that the variation of slope with temperature depends on the frequency region, which is not predicted by HOB model.

In summary we can say that both QMT and HOB models fail to give a strong temperature dependence of conductivity which starts at higher temperature for higher frequency. None of these can account for the slopes of the order of 0.5 observed for several decades of frequency.

5. Two regions of AC conductivity

The measured $\sigma_m(\omega)$ and $\epsilon'(\omega)$ as a function of temperature and fixed frequencies are shown in figures 9 and 10 respectively (Mansingh *et al* 1980a). Variations of $\sigma_m(\omega)$ and $\epsilon'(\omega)$ as a function of frequency and for fixed temperatures are shown in figures 7, 8 and 11, 12 respectively. Similar variations of $\sigma_m(\omega)$ as a function of frequency and temperature has been reported for several other amorphous materials (Mott and Davis 1979). However, very few studies report $\epsilon'(\omega)$. A close look of the figures suggest that we can separate the following two distinct regions of the variations of $\sigma(\omega)$ and $\epsilon'(\omega)$ as a function of temperature and frequency.

5.1. Region where measured ac conductivity approaches dc conductivity

It is evident from figure 9 that $\sigma_m(\omega)$ at a given frequency ultimately becomes equal to σ_{dc} , according to equation (4) at the temperature where this equality occurs $\sigma(\omega)$ or ϵ'' becomes equal to zero. Hence a peak in ϵ'' is expected at

Figure 9. Total measured conductivity σ plotted against $1000/T$ for fixed frequencies of measurements for 81/19 tungsten phosphate glass.

Figure 10. Measured dielectric constant of 67/33 tungsten phosphate at four fixed frequencies as a function of frequencies.

Figure 11. The variation of dielectric constant with frequency for a 67/33 tungsten phosphate glass at four fixed temperatures.

Figure 12. Measured dielectric constant as a function of frequency at room temperature for the three $\text{WO}_3\text{-P}_2\text{O}_5$ glasses. The theoretical plot for $\alpha = 0$ and $\alpha = 0.5$ for 80% glass is also shown.

a temperature slightly lower than the temperature where $\sigma_m(\omega)$ becomes equal to σ_{dc} at a given frequency. However, such a peak in ϵ'' may be due to the different temperature dependence of $[\sigma(\omega) \propto T]$ and $\sigma_{dc} \propto [\exp(-\Delta E_{dc}/kT)]$. At some temperature σ_{dc} is expected to be very much greater than $\sigma_m(\omega)$ at a given frequency, and so the measured $\sigma_m(\omega)$ within the accuracy of measurements (Mansingh *et al* 1975a) will appear equal to σ_{dc} . A clear indication that these loss peaks are real comes from the dielectric constant measurements.

In the region where $\sigma_m(\omega)$ approaches σ_{dc} , ϵ' shows a rapid increase with temperature after reaching a peak value it shows a small decrease with temperature (figure 10). This behaviour is consistent with the Debye-type dispersion with well-defined dielectric loss peaks. According to equation (8) at lower tempera-

tures, the measuring frequency f_m is expected to be very much higher than the relaxation frequency f_0 , and so $\epsilon'(\omega)$ will be close to ϵ_∞ . When the temperature increases f_0 increases and approaches f_m which causes a rapid increase of $\epsilon'(\omega)$ with temperature. At high temperatures where $f_0 \gg f_m$ $\epsilon'(\omega)$ will become equal to ϵ_0 . A peak in ϵ_0 indicates that the static value has been reached and ϵ_0 decreases with increasing temperature. The variation of $\epsilon'(\omega)$ with frequency is also consistent with Debye-type dispersion with well-defined loss peaks.

Analysis of the results in terms of the conventional Colé-Cole plots to determine whether the loss peak, is due to a single relaxation time or a distribution of relaxation times, is difficult because in the region of peak in ϵ'' , $\sigma_m(\omega)$ is close to σ_{dc} and even small errors in the measured $\sigma_m(\omega)$ and σ_{dc} will cause very large errors in the derived ϵ'' . To overcome this a method has been suggested (Mansingh *et al* 1980a; Mansingh *et al* 1972) to determine the relaxation frequency and distribution parameter from the measured dielectric constant alone. The reduced plots $\log(\epsilon'(\omega) - \epsilon_\infty)/(\epsilon_0 - \epsilon_\infty)$ vs $\log(\omega\tau)$ for V_2O_5 - P_2O_5 glasses (Mansingh *et al* 1972) is shown in figure 13. The theoretical plots corresponding to different values of a from equation (12) show that there is a distribution of relaxation times and distribution parameter is independent of temperature.

A plot of $\log f_0$ vs $1/T$ is shown (Mansingh *et al* 1980a) in figure 14. The activation energy from such plots have been found equal to that derived from

Figure 13. Reduced plot of dielectric constant ϵ' at different frequencies and temperatures for 80% V_2O_5 - P_2O_5 glass. The dotted curves represent the theoretical values for different values of distribution parameter a .

Figure 14. Plot of relaxation frequency $f_0 = 1/2 \pi \tau$ versus $1000/T$ for the three tungsten phosphate glasses.

dc conductivity in transition metal ion phosphate glasses. A close correlation between activation energies from dc conductivity and dielectric loss peaks is demonstrated (Sayer *et al* 1971) in figure 15 where $\log f_0$ and $\log \sigma_{dc}$ have been plotted together against $1/T$.

All the features of dielectric dispersion observed in dielectric relaxation studies (§ 3) are present in the temperature region where measured ac conductivity approaches dc conductivity. Measurement of $\epsilon'(\omega)$ as a function of sample thickness (Mansingh *et al* 1980a) has shown that dielectric constant over the entire frequency and temperature region is independent of thickness. A plot of ϵ_0 vs $1/T$ (Mansingh *et al* 1980a) is shown in figure 16, the intercept at $T \rightarrow \infty$ is close to ϵ_∞ , the measured dielectric constant at 77 K. This as discussed in § 3.2 suggests that the dielectric relaxation is most probably a bulk effect.

A distribution of relaxation times which gives a broad but well-defined dielectric loss peaks, cannot give a slope of 0.8 as the tail of the loss peaks (Mansingh *et al* 1980a).

5.2 Region where ac conductivity is substantially higher than dc conductivity

In the temperature region 77 K to 100 K $\sigma(\omega)$ shows almost a linear dependence on temperature and $\epsilon'(\omega)$ is almost independent of temperature at all the frequencies. The slope at higher frequencies and higher temperature (figure 8) is not lower than that at low temperatures and low frequencies (figure 7). Hence we can represent

$$\sigma_2(\omega) = BT\omega^s, \quad (24)$$

Figure 15. A comparison of the temperature dependence of the relaxation frequency estimated from the temperature at which the peak in ϵ'' occurs at frequency f_0 and the temperature dependence of the dc conductivity for an 80/20 V_2O_5 - P_2O_5 glass.

Figure 16. Plot of static dielectric constant ϵ_0 against $1000/T$ for the three tungsten phosphate glasses.

where B and s are parameters of the system and are expected to be almost independent of temperature. The inadequacy of different models suggested for this region have been discussed in § 4. The empirical equation (24) is similar to QMT models discussed in § 4.1, but it can take different values of slope. However, the distribution of relaxation times for this mechanism is expected to be large

so that s lies approximately between 0.8 and 1, and as discussed in § 2 a well-defined dielectric relaxation time or dielectric loss peak cannot be assigned to such a system. Probably this mechanism is due to electronic hopping in all the systems. This has been shown (Webb *et al* 1978) for β -AgI, but more studies are needed for other ionic materials. The slope s at 77 K and at high frequencies and room temperature (figures 7, 8) are greater than 0.8 and so one would have not expected a well-defined loss peak for $\text{WO}_3\text{-P}_2\text{O}_5$ glasses.

6. Model of two mechanisms for ac conductivity

The above discussions show that there are two distinct regions of ac conductivity. A well defined but broad dielectric loss peaks are observed in one region and a sub-linear frequency-dependent conductivity in the other. However, the two regions cannot be divided simultaneously on both temperature and frequency regimes. Hence the ac conductivity at any temperature may be expressed as (Mansingh *et al* 1980a; Pollak 1971, 1976)

$$\sigma(\omega) = \sigma_1(\omega) + \sigma_2(\omega) = \int_0^{f_1} \frac{g_1(\tau) \omega^2 \tau}{1 + \omega^2 \tau^2} d\tau + \int_{f_1}^{\infty} \frac{g_2(\tau) \omega^2 \tau}{1 + \omega^2 \tau^2} d\tau \quad (25)$$

The mechanism responsible for $\sigma_1(\omega)$ gives a broad but well-defined dielectric loss peaks and one of the many distribution functions can be suggested (Hill *et al* 1969; McCrum *et al* 1967) for $g_1(\tau)$. The upper limit of frequency f_1 upto which contribution from $\sigma_1(\omega)$ dominates depends on the width of distribution of relaxation times in $g_1(\tau)$. It has been shown (Mansingh *et al* 1980a) that in $\text{WO}_3\text{-P}_2\text{O}_5$ glasses $\sigma_1(\omega)$ dominates upto about three decades above f_0 , the average relaxation frequency. For a single relaxation time (ω^2 frequency dependence) envisaged in HOB model f_1 will be approximately equal to f_0 . However, a well-defined relaxation time in amorphous systems has not been observed in the majority of dielectric relaxation studies discussed in § 3. Since dielectric loss peaks are usually broad the tail of these broad loss peaks may give a slope of the order of 0.5 (§ 2) for several decades of frequency. It has been shown that a slope of 0.5 in VO_2 crystals can be accounted by well-defined and broad dielectric loss peaks (Mansingh *et al* 1978a).

The mechanism responsible for $\sigma_2(\omega)$ gives almost a linear or sublinear ($0.8 < s < 1$) dependence of conductivity on frequency. The inadequacy of different functions suggested for $g_2(\tau)$ to get expressions similar to (25) for $\sigma_2(\omega)$ has already been discussed in § 4. Pollak (1976) suggested upper frequency limit for $\sigma_2(\omega)$ also but there is controversy in experimental observation and comparatively few studies have been reported and so we ignore it.

6.2. The temperature dependence of ac conductivity

It has already been pointed out that both QMT and HOB models fail to give the observed temperature dependence of $\sigma(\omega)$. Let us see how the model of two mechanisms can explain the temperature dependence of $\sigma(\omega)$.

We shall assume that $\sigma_1(\omega)$ can be expressed by (12) and $\sigma_2(\omega)$ by (24). The value of B and s in (24) can be found from the measured values at 77 K. The values at different frequencies and temperatures can be calculated from the known values of B and s . The calculated values are shown by dotted lines in figure 17, for a $\text{WO}_3\text{-P}_2\text{O}_5$ glass. It may be noted that $\sigma_2(\omega)$ can account for measured $\sigma_m(\omega)$ upto higher temperatures for higher frequencies. However, at a given frequency $\sigma_m(\omega)$ is much higher than that expected due to $\sigma_2(\omega)$ after a particular temperature and the deviation increases with increasing temperature.

The contribution of $\sigma_1(\omega)$ can be calculated by assuming a temperature-independent value of $a = 0.5$ for TMI phosphate glasses and $\epsilon_\infty = 14$ (for $\text{WO}_3\text{-P}_2\text{O}_5$ glass). The values of f_0 and ϵ_0 at different temperatures can be known from figures 14 and 16, respectively. Substituting these known values in equation (12), $\sigma_1(\omega)$ at different temperatures and frequencies can be calculated. The calculated values are shown in figure 17 by chained lines.

The sum of two contributions $\sigma_1(\omega)$ and $\sigma_2(\omega)$ is shown by solid lines, and the experimental points by circles. Considering the fact that $\sigma_1(\omega)$ has been calculated from only the measured values of $\epsilon'(\omega)$ and $\sigma_2(\omega)$ from the measured values of 77 K, the agreement between theoretical and experimental values can be taken as satisfactory.

The above discussions show that the temperature dependence of $\sigma(\omega)$ can be adequately explained by taking two mechanisms of conduction or combining the approaches of workers from dielectrics and semiconductor schools.

Figure 17. The circles show the experimental ac conductivity for 67/33 glass at different frequencies and temperature derived by subtracting dc conductivity from the measured conductivity. The chained line shows the contribution of $\sigma_2(\omega)$ calculated from equation (12). The dotted line gives the contribution $\sigma_1(\omega)$ calculated from equation (2). The solid line shows the sum of the two calculated values $\sigma_1(\omega) + \sigma_2(\omega)$.

6.3. Physical model for two mechanisms

The contribution of $\sigma_2(\omega)$ is expected to dominate at low temperatures, however at high frequencies substantial contribution may be present even at high temperatures. The origin of $\sigma_2(\omega)$ has been associated to the hopping of carriers in the localized states nor the Fermi level. $\sigma_1(\omega)$, which is responsible for activated dielectric loss peak has been associated (Koichi *et al* 1978; Mansingh *et al* 1975b) to hopping of the carriers excited to the localized states in conduction band tails. However, this association is not quite obvious, because from the models discussed in § 3, one would expect the localized state to be separated by high potential barrier having narrow distribution for activated dielectric loss peaks. In transition metal oxide glasses the formation of polaron bands (Hench 1970), $\sigma_2(\omega)$ has been associated with tunnelling and $\sigma_1(\omega)$ by hopping over the barrier (Mansingh *et al* 1980a). Pike (1972) and Elliot (1977, 1978) have associated $\sigma_1(\omega)$ with the excitation of electrons to conduction band. However, dipolar polarization and dielectric loss peaks, due to bulk effect, cannot be visualized in conventional band conduction, and there is no evidence of such peaks in conventional band semiconductors.

The model of random potential wells can be used to qualitatively explain (Mansingh *et al* 1978b; Sayer *et al* 1978) the origin of two mechanisms of conduction. However, before speculating about more realistic physical models, it will be useful to see whether the model of two mechanisms is applicable to other amorphous films and bulk glasses or not. This requires detailed investigation of dielectric constant in the region where $\sigma_m(\omega)$ approaches σ_{dc} , or dielectric relaxation studies.

7. Conclusions

The models for dielectric relaxation, which suggest well-defined dielectric loss peaks by workers from dielectric school have been briefly reviewed. The importance of low frequency saturation dielectric constant in differentiating the spurious phenomenon from the bulk phenomenon is pointed out. The models for ac conductivity suggested by workers from semiconductor school are also discussed. It is shown that none of the models suggested so far can adequately explain the experimental results. The model of two mechanisms, which considers that activated dielectric loss peaks [$\sigma_1(\omega)$] and frequency-dependent conductivity [$\sigma_2(\omega)$] originate from different mechanisms can qualitatively explain the temperature dependence of ac conductivity in transition metal ion phosphate glasses, by taking empirical expressions for $\sigma_1(\omega)$ and $\sigma_2(\omega)$. A satisfactory model for the two mechanisms of $\sigma(\omega)$ in conventional band diagram of amorphous semiconductors is lacking.

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