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Ultrasonic attenuation in commercial lead–silicate glasses

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The ultrasonic attenuation of a range of commercial lead–silicate glasses has been studied over the temperature range 4.2 to 360 K. Measurements of shear-wave ultrasonic attenuation, A, over the frequency range 5 to 50 MHz have revealed peaks in the attenuation below room temperature and these are interpreted in terms of the resonant movement of oxygen ions in the silica networks. In some cases the effects of the peaks are seen to extend to room temperature in some of these glasses. Frequency dependence of the attenuation, A, can be fitted to a relation of the form $A \propto F^N$, where F is the frequency and N is a constant. Shear-wave velocities are also measured to aid characterization of the glasses.

1. Introduction

Glasses used in ultrasonic delay lines are usually mixtures of PbO and SiO_2 with various network modifiers and other traces added to render the glass more readily manufacturable. A careful choice of the constituents is vital to produce a delay time that is temperature independent over as wide a range of temperature as possible. The temperature independence of the delay time (or isopausticity) is, however, only obtained at the expense of relatively high values of ultrasonic attenuation at room temperature. The attenuation is sufficiently high to limit the application of the delay lines to frequencies below 10 MHz.

It is well known that oxide glasses have a large ultrasonic attenuation peak at low temperature [1]; for example, the peak in silica occurs at about 50 K at 20 MHz [2–4] while that for B_2O_3 is at 150 K [5]. It is now generally believed that the peaks originate in the movement of oxygen atoms in the glass structure between two equivalent sites. The relaxation time associated with the movement causes a resonant absorption of energy from an ultrasonic beam at a temperature which depends on the frequency of the ultrasound.

The purpose of the present paper is to study the low-temperature peaks of various commercial PbO–SiO_2 glasses to ascertain whether the peak has any influence at room temperature on the ultrasonic attenuation. The frequency dependence of the attenuation of the glasses has also been measured and compared with that of silica. Commercial glasses were chosen for the study since early attempts to produce small homogeneous samples of binary PbO–SiO_2 glasses met with difficulty. The commercial glasses are made in very large melts and are highly homogeneous.

In the present study we have restricted our attention to shear acoustic waves since it is this acoustic mode that is used in delay-line devices. The shear wave has a lower velocity and hence requires less material volume for a given acoustic delay. Previous work has shown that the shear and longitudinal attenuation peaks have very similar temperature and frequency dependence [1].

2. Experimental techniques

The glasses studied are listed in Table I together with their compositions in molar percentages.

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TABLE I Composition of glasses (analysed chemically except where shown)

Glass type	Composition (mol %)														
	SiO_2	PbO	K_2O	Na_2O	BaO	B_2O_3	Fe_2O_3	Al_2O_3	Sb_2O_3	SO_3	CdO	CeO_2	CaO	SrO	As_2O_3
Pilkington CDL1	72.7	13.5	2.2	5.4		1.4	Trace	2.3	0.1				2.2	0.2	
Corning 8875	73.2	18.9	7.9												
Hoya DLB 5510*	68.7	15.6	7.1	0.3		7.2	Trace	1.0	0.5						0.1
Schott UDL7†	74.9	19.1	0.5	0.9	3.9		Trace	Trace	0.1		0.6		Trace		
Bausch Lomb T-40‡	75.0	15.9	9.1												
Pilkington RW26	68.6		7.5	9.9	5.0	6.7	Trace	1.4				0.8		0.1	
Pilkington RW62	49.3	49.6		1.1			Trace								
Pilkington DBC 620603	45.0			0.6	29.6	21.7	Trace	1.7	0.1	0.3			0.2	0.8	Trace

*No ultrasonic measurements taken in present work.

†Estimated values.

‡Nominal values.

Since the parallelism of the samples and the bonding of transducers to the parallel surfaces are crucial, considerable care was given to the grinding and polishing of the specimens. Glass samples approximately 2 cm in diameter and 1 cm in thickness were lapped and polished flat to within $\lambda/10$ and parallel to within two seconds of arc. The polished surfaces were prepared using diamond particle abrasives on a standard lapping machine. Diamond was chosen for two reasons: firstly, diamond abrasives are more accurately graded than conventional abrasives and, secondly, diamond provides a faster cutting time and is more wear-resistant than conventional abrasives. Surfaces produced by diamond tend to be more uniform and have a smoother profile (it is possible to obtain semi-polished surfaces with relatively large particle sizes such as 6 μm and even 14 μm. This allows for a check on the flatness to be made during part of the lapping or truing process) and only a small amount of diamond has to be added to the lapping plate occasionally, rather than a continuous feed of slurry; this simplifies the polishing procedure. The finish obtained was more than adequate for ultrasonic measurement.

A typical polishing procedure adopted was as follows. The sample was initially lapped on a brass lap with 14 μm diamond abrasive. After achieving a matt finish the sample was transferred to a soft metal lap of lead impregnated with 14 μm diamond. Brief lapping produced a semi-polish that allowed the flatness to be checked by standard interferometric techniques. Alternation between these two laps produced the basically flat surface. To improve the flatness and quality of the finish the sample was cleaned and transferred to a solder plate impregnated with 6 μm diamond particles. The finish achieved in this way was normally sufficient, but if further polishing was necessary, an electroplated tin lap impregnated with 1 μm diamond was used.

Preparation of parallel faces was achieved by means of a polishing jig* based on jigs designed by Fynn and Powell [6] and Bennett and Wilson [7] and a standard optical autocollimator. The major problems in lapping and polishing arose when working on softer, high lead-content glasses. These tended to increase the wear of the lead plates and, as a consequence, the loading of the specimens was found to be very critical. Usually, convex specimens resulted, irrespective of the position of the jig on the polishing plate. One solution was to reduce the load on the specimen to a minimum. This, however, had the effect of greatly increasing the polishing time. A method using wax laps [8] was found to overcome these problems. The specimens were lapped on the brass plates using aloxite abrasives instead of diamond. After using 125 grade abrasive, the jig was placed on a prepared flat and grooved wax lap and a colloidal silica abrasive used. A small peristaltic pump recirculated the abrasive on the lap. It was found necessary to use higher lap speeds than for diamond but a reasonably-flat polished surface with minimal edge turn-down was obtained. For further discussion of the preparation of the various laps required the reader is referred to more detailed descriptions [9].

Great care was taken over the lapping of the samples to ensure that the opposite faces were parallel and hence reduce the errors introduced, particularly at high frequencies, by the wedging of the sample.

In many cases difficulties were encountered in bonding the transducers to the samples. Many bonding agents were employed, with Dow Resin 276-V9 and No–Naq stop-cock grease being the most successful of the readily demounted bonds, and "Permabond 102" being the most successful of the more permanent materials. This adhesive had a setting time of 30 sec but needed to be left for 24 h to reach maximum strength. It had the further advantage that acetone could be used as a solvent. The major problem with the bonding of the transducers is probably associated with the very large thermal expansions present in these glasses at low temperatures. In some cases, using Permabond, it was noted that the glass itself fractured, not the bond or the transducer.

The temperature was varied using a standard helium cryostat and measured using a 0.03 at% Fe in Au against chromel thermocouple to an absolute accuracy of ± 1 K. All the glasses were measured in the as-received state with no subsequent annealing.

The ultrasound was generated by 5, 10 or 15 MHz quartz plates operating either at their fundamental frequency or at higher harmonics. The quartz transducers were excited by an r.f. pulse generator and the attenuation was measured by comparison with a variable, calibrated, expo-

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*Supplied by Metals Research Ltd, UK.

nential decay with a point-to-point sensitivity of at least 0.02 db μsec^{-1}. Echo trains were always sufficient to allow the measurement of the velocity of sound but great care and patience had to be exercised to obtain exponential echo trains over the whole temperature range.

Ultrasonic velocity was measured using the pulse echo overlap technique with an absolute accuracy of ± 0.25% and a point-to-point sensitivity of 3 in 10^5.

TABLE II Coefficient of attenuation, N, for the glasses at room temperature (see Equation 1)

Glass	N
RW62	1.21
DBC 620603	1.23
CDL1	1.24
UDL7	1.18
DLB 5510	1.09
T-40	1.27
Silica	2.02
8875	1.03

3. Results

The frequency dependence of the shear-wave ultrasonic attenuation at room temperature for the glasses in Table I is shown in Fig. 1, where it is compared with that for pure silica [4] and the isopaustic delay-line glass Bausch and Lomb T-40 [10]. The composition of T-40 is also given in Table I and contains 50 wt% SiO_2, 39.5 wt% PbO and 9.5 wt% K_2O.

No corrections have been made for ultrasonic diffraction effects: such corrections would tend to lower the attenuation at low frequencies. However, theoretical analysis of the shear-wave case [11] has been restricted to two dimensions and it is difficult to estimate actual losses for the real three-dimensional situation. Since the wavelength determines the degree of diffraction for a particular transducer and specimen size, increasing the frequency will reduce the diffraction effects. Furthermore, the specimen attenuation increases with frequency, so eventually, the specimen attenuation masks the effect of diffraction. The attenuation of the lead–silicate materials is

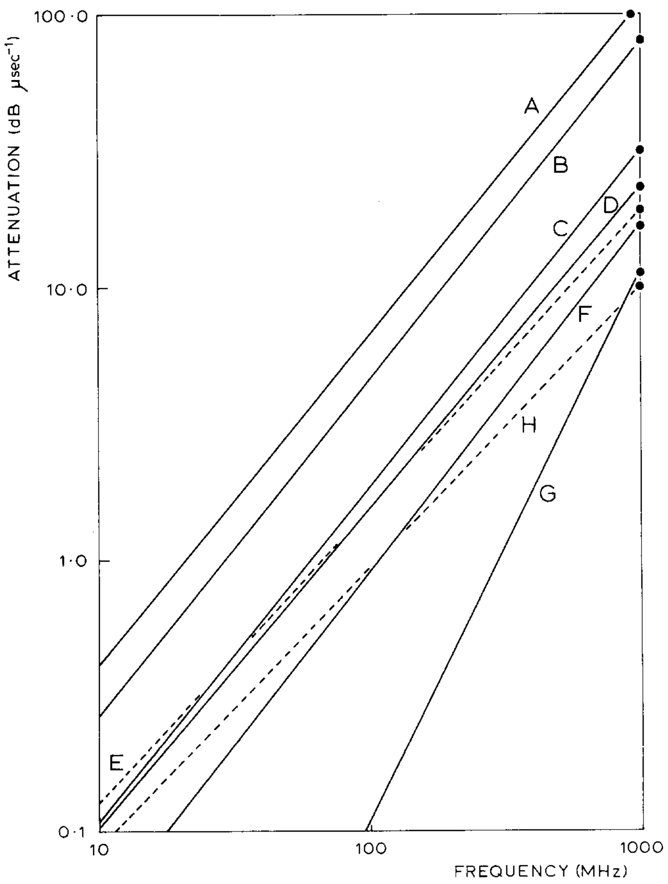

Figure 1 Shear-wave ultrasonic attenuation (in db μsec^{-1}) as a function of frequency for a range of lead silicate commercial glasses. A: Pilkington RW62; B: Pilkington DBC 620603; C: Pilkington CDL1; D: Schott UDL7; E: Hoya DLB 5510; F: Bausch and Lomb T-40 [10]; G: Silica [4]; H: Corning 8875.

inherently high and coupling this with the sample and transducer diameters of 2 cm and 1 cm, respectively, indicates that corrections for diffraction above 20 MHz will not be necessary.

The frequency dependence of the attenuation can be expressed in the form

$$A = Bf^N, \tag{1}$$

where f is the frequency and B and N are constants for a particular glass. Table II lists values of N for the glasses considered here together with silica and T-40. At low frequencies, the glasses split into three groups, those with very low SiO_2 concentration have the highest attenuation, pure SiO_2 has low attenuation and the SiO_2–PbO mixtures with approximately 75 mol% SiO_2 have intermediate attenuation. Values of N are roughly similar for all the glasses except SiO_2. It is noticeable that N for RW62 glass and DBC 620603 glass are almost identical indicating that the replacement of PbO by an equal molar percentage of a range of oxide glasses has little effect on the frequency dependence at room temperature. Hoya DLB5510 and Corning 8875 glasses have the lowest values of N, but nothing in their compositions immediately explains this behaviour. The only difference between these two glasses and Schott UDL7 glass is the presence of appreciable amounts of K_2O; but T-40 also has 9.1 mol% K_2O and a frequency dependence very similar to UDL7.

The temperature dependences of the ultrasonic shear-wave attenuation for a range of frequencies, are shown in Figs 2 to 8 for the glasses listed in Table I. The frequency range was limited to 50 MHz due to the inherently high attenuation in these materials at higher frequencies. (The breaks in the curves are due to difficulties encountered in the transducer–sample coupling already mentioned.) In all cases there is a maximum in the attenuation below room temperature, the maximum is either independent of frequency or shifts slightly to higher temperature as the frequency is increased. The attenuation in all cases is dominated by this broad loss peak throughout the whole temperature range.

We will consider first the two non-isopaustic glasses that contain relatively small amounts of SiO_2.

The temperature dependence of RW62 (Fig. 2) indicates the effect of adding 78.6 wt% of lead oxide to SiO_2. The peak in the attenuation has moved from 50 K in pure silica to approximately 100 K and the decay of the peak on the high-temperature side is much slower than for silica. At 15 MHz and at higher frequencies the temperature dependence, dA/dT, at room temperature is the same as it is at 150 K indicating that the resonance peak is still having a marked effect at 300 K.

In the case of DBC 620603 glass (Fig. 3), where the PbO has been replaced in the main by BaO and B_2O_3, the maximum in the attenuation has shifted to approximately 150 K although its magnitude is less than for the RW62 glass. The decay of the attenuation as the temperature increases above 150 K is more rapid for DBC than for RW62, but there is still considerable attenuation at 300 K that has its origin in the tail of the peak. It is noticeable that A for RW62 and DBC 620603 has a small change in slope at approximately 50 K for frequencies of above 15 MHz.

The isopaustic glass, Corning 8875, has a totally different behaviour (Fig. 4). The attenuation peak is centred about 45 K at 5 MHz rising to 50 K at 35 MHz. The peak is relatively sharp and narrow, similar to that for pure silica. For comparison, the curve for silica is also plotted in Fig. 4 for measurements at 20 MHz. The low-temperature side of the peak is almost the same in both materials. However, on the high-temperature side the silica attenuation falls off more rapidly. In addition, there is a hint of a shoulder in the curve at 100 K, particularly at 15 MHz. The shoulder occurs at the same temperature as the peak in RW62 (Fig. 2). The high room-temperature attenuation in 8875 glass also bears some similarity to RW62, which has a very broad maximum extending well above 300 K.

The other three isopaustic glasses, Pilkington CDL1, Schott UDL7 and Hoya DLB5510 behave in a manner similar to each other, see Figs 5 to 7. A peak in the attenuation occurs in the region of 50 K and at higher frequencies in particular, there is a shoulder that extends above 100 K. In the case of the Hoya and Schott glasses, the shoulder is marked at 35 MHz and quite marked for the Schott glass at 25 MHz. On the other hand, there is no evidence in CDL1 glass of a shoulder at frequencies lower than 45 MHz. Finally, the RW26 (Fig. 8), which contains a high quantity of SiO_2 but no PbO, has a peak at 50 K although the high-temperature decay of the attenuation is much slower than for SiO_2.

Fig. 9 shows the variation of attenuation of 10, 30 and 100 MHz shear waves at room temperature

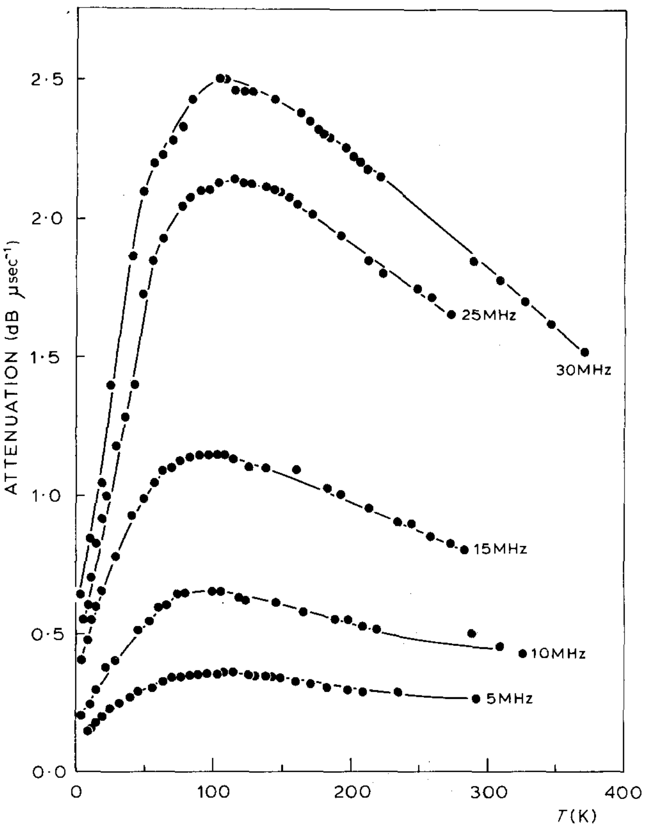

Figure 2 Shear-wave ultrasonic attenuation as a function of frequency and temperature for Pilkington RW62 glass.

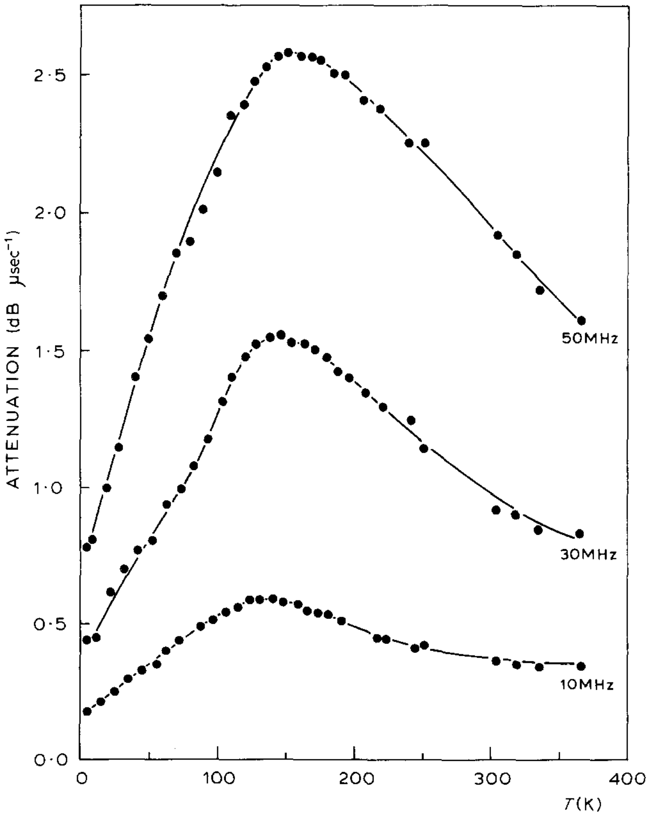

Figure 3 Shear-wave ultrasonic attenuation as a function of frequency and temperature for Pilkington DBC 620603 glass.

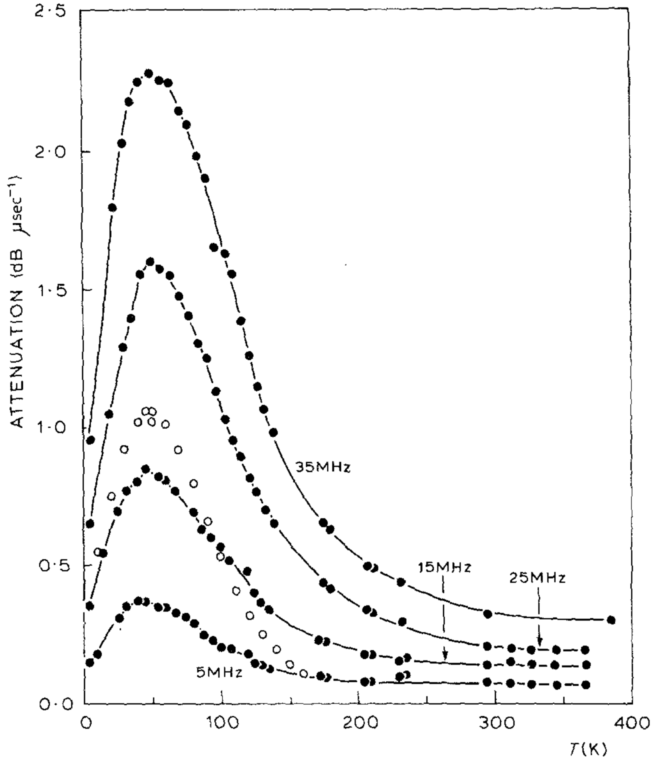

Figure 4 Shear-wave ultrasonic attenuation as a function of frequency and temperature for Corning 8875 glass, silica [4] is shown for comparison at 20 MHz (open circles).

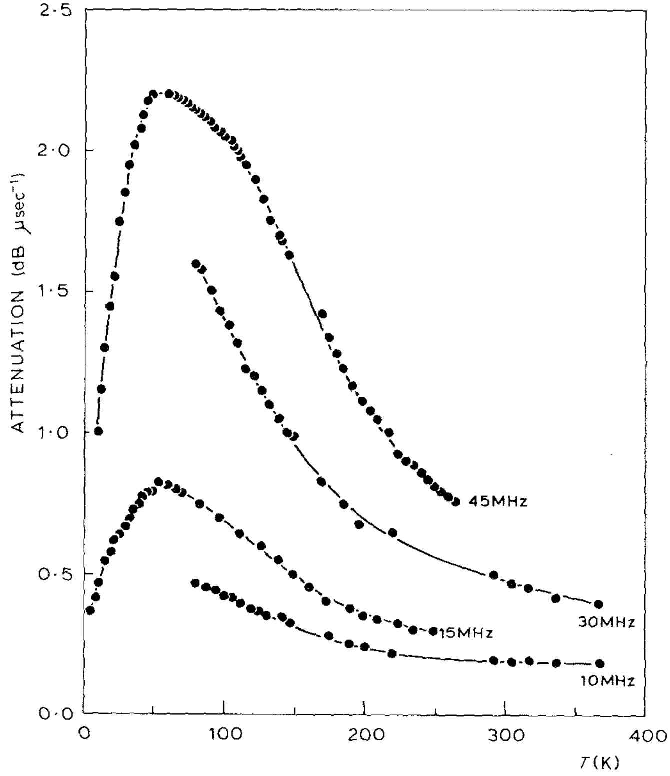

Figure 5 Shear-wave ultrasonic attenuation as a function of frequency and temperature for Pilkington CDL1 glass.

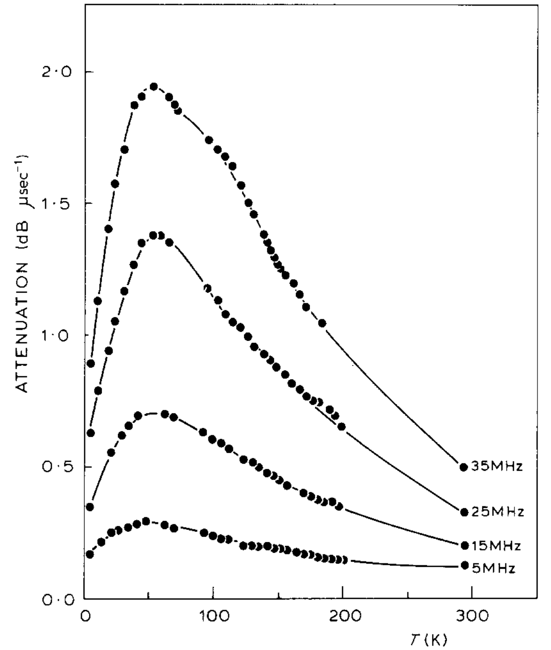

Figure 6 Shear-wave ultrasonic attenuation as a function of frequency and temperature for Schott UDL7 glass.

with SiO_2 molar concentration. A log–log relationship is indicated at each frequency but many other lead–silicate structures should be examined before any conclusions can be drawn.

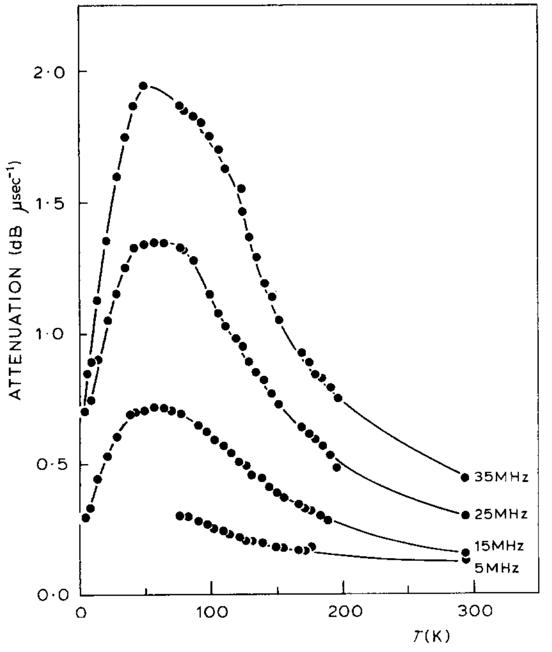

Figure 7 Shear-wave ultrasonic attenuation as a function of frequency and temperature for Hoya DLB5510 glass.

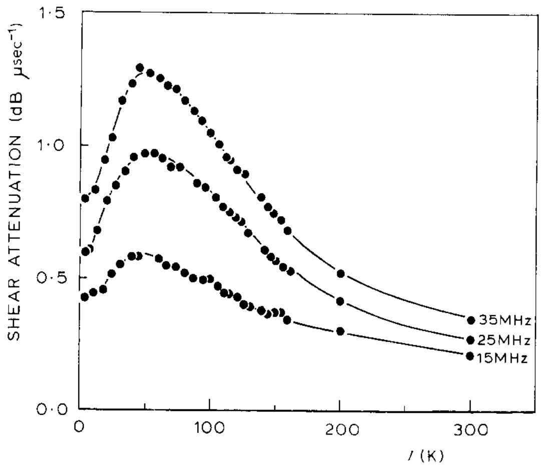

Figure 8 Shear-wave ultrasonic attenuation as a function of frequency and temperature for Pilkington RW26 glass.

Fig. 10 shows the temperature dependence of shear-wave velocity for the different glasses. It is evident that for the three non-isopaustic glasses there is no region where the shear-wave velocity is independent of temperature (Fig. 10a, b and g) while for the four glasses developed for isopaustic behaviour, the temperature invariance extends over a wide range (Fig. 10c, d, f and g) about room temperature. No attempt has been made to correct for thermal expansion so it is the apparent velocity that is being measured and represented in Fig. 10. In the isopaustic region a decrease in the real velocity, as temperature is lowered, is accompanied and matched by a decrease in sample dimension.

4. Discussion

In the glasses listed in Table I, SiO_2, B_2O_3 and As_2O_3 are network formers. Intermediates, whose oxides alone do not form glasses but may take part in forming the glass network with one of the primary glass formers are, for example, PbO, Al_2O_3 and CdO in the samples measured here. Oxides such as Na_2O, K_2O, CaO and BaO, whose metallic ions occupy the large interstices of a glass network, are network modifiers.

The rôles of the network forming, modifying or intermediate constituents in determining the ultrasonic attenuation of glasses are not well understood. The loss peaks observed in this study arise from a structural relaxation mechanism or mechanisms with a distribution of activation energies. The peak in SiO_2 occurs at 50 K and has a full-width-at-half-height of approximately 90 K while B_2O_3 has a peak occurring at 71 K [5] and a full-width-at-half-height of about 270 K; this

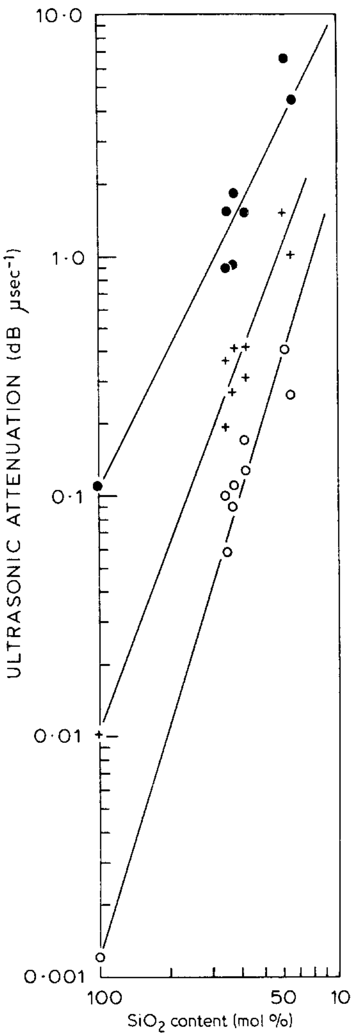

Figure 9 The variation of the room-temperature shear-wave ultrasonic attenuation of a range of lead–silicate glasses with molar silica concentration. ○ 10 MHz; △ 30 MHz; ● 100 MHz.

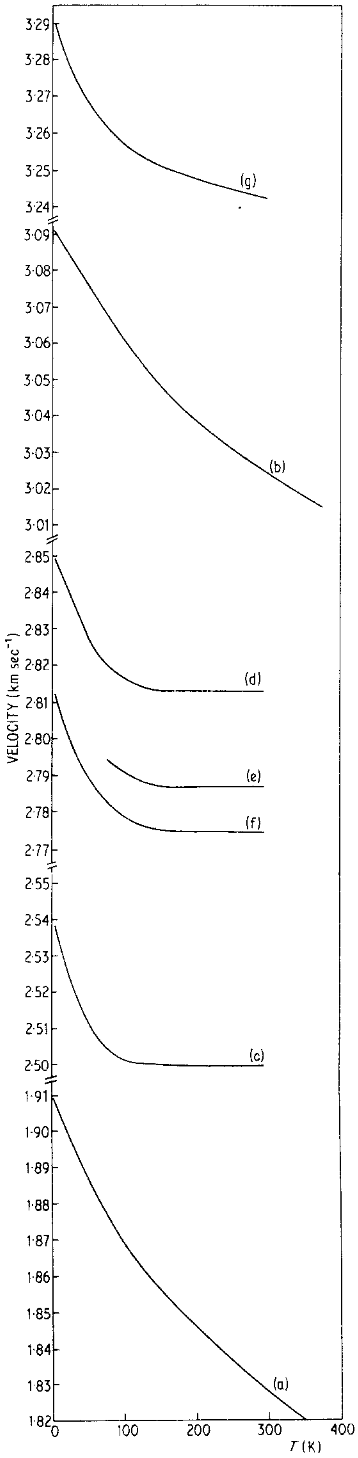

Figure 10 The variation of the shear-wave velocity with temperature for the glasses in Table I. (a) RW62; (b) DBC 620603; (c) Corning 8875; (d) CDL1; (e) Schott UDL7; (f) Hoya DLB5510; (g) RW26.

suggests a wider range of activation energies for the loss mechanism in B_2O_3. Glasses formed from the mixtures of SiO_2 and B_2O_3 [12] have higher attenuation at all temperatures than the individual constituents and the peak is observed at a higher temperature. This perhaps indicates that there is a higher concentration of ultrasound absorption centres in the two-component glass, and these ultrasound absorption centres are the non-linear, bridging oxygen X–O–X bonds where X is either Si or B. The X–O–X bonds may well have a wider range of angles in the multi-component material than in single-component glasses.

The addition of the network modifier Na_2O to the SiO_2–B_2O_3 glasses has been found to reduce

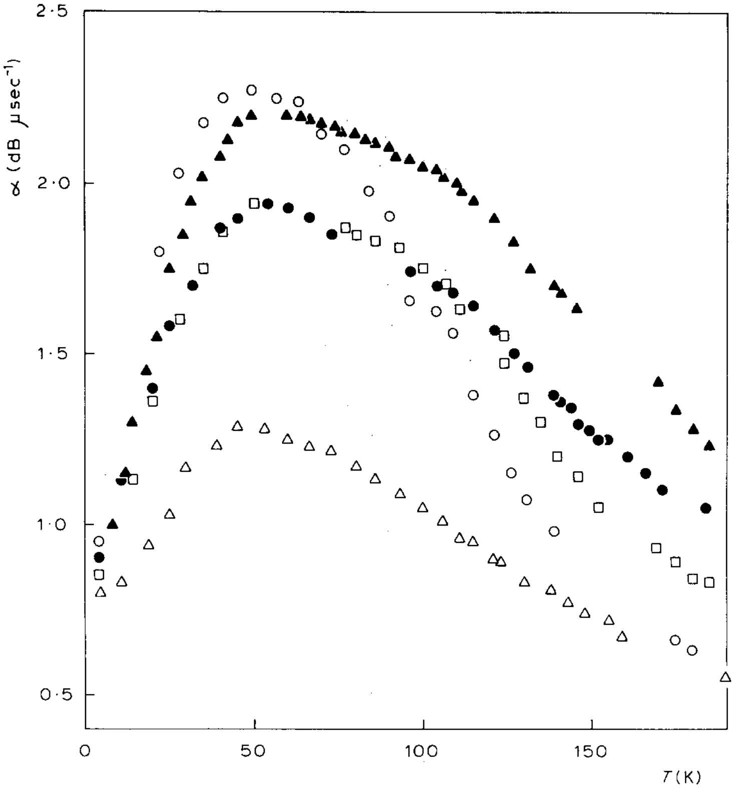

Figure 11 The temperature dependence of the shear-wave ultrasonic attenuation for a range of glasses at 35 MHz: ○ Corning 8875, ● Hoya DLB5510, □ Schott UDL7, △ Pilkington RW26; and at 45 MHz: ▲ Pilkington CDL1.

both the height of the attenuation peak and its temperature [12]. For example, the peak height decreases linearly with Na_2O content up to at least 10 mol%. Maynell *et al.* conclude that, on addition of Na_2O, the acoustic absorption centres associated with the B–O–B bridges are being removed. The Na_2O is thought to increase the boron atom co-ordination number from 3 to 4 which leads to an increased number of bridging oxygen ions; the presence of Na^+ cations may impede the movement of the oxygen atoms and thus decrease the acoustic loss. Any affinity of Na_2O and presumably K_2O species for boron sites in the glass network is not in evidence in the present experiments since the CDL1, Hoya and Schott isopaustic glasses have very similar behaviour at, for example, 35 MHz (Fig. 11). The CDL1 and Hoya glasses have an almost identical molar percentage of the alkali oxide but different concentrations of B_2O_3 while the Schott glass has no B_2O_3 and very little Na_2O or K_2O. However, such conclusions are very uncertain given the complicated composition of the glasses studied.

The work of Maynell *et al.* [12] indicates that, in glasses, the network formers, the network modifiers and the intermediates such as PbO all affect the attenuation of ultrasound and its temperature dependence. X-ray diffraction measurements [13] and Raman spectroscopy [14] have both confirmed the ease with which Pb ions enter the glass network, at least in glasses with a high lead content. In particular, Mydlar *et al.* [13] report strong X-ray evidence that the Pb ions are acting as network formers at 33 mol% PbO and are taking regular positions in the silica chains at 50 mol% PbO. Recent density measurements [15] on $PbO–SiO_2$ glasses suggest strongly that at 21 mol% PbO the lead ions are taking substitutional positions in the network.

In the present experiments the behaviour of RW62, a glass with a one-to-one molar mix of PbO and SiO_2, is in keeping with the results of Mydlar *et al.* [13]. The resonance peak at 50 K due to Si–O–Si bonds has been almost completely destroyed and replaced by a broad peak at approximately 100 K. The attenuation at 300 K is still more than 50% of its peak value. This shifted and broadened resonance peak is probably produced by modified Si–O–Si and new Pb–O–Si bonds where the modifications to the silica chains are due to Pb ions entering the network.

If the four isopaustic glasses are considered in the same way, they have PbO concentrations ranging from 13.5 to 19.1 mol%. One would therefore expect the majority of Pb ions to be network modifiers rather than network formers. All these glasses have a peak attenuation at 50 K due to the Si–O–Si resonance although this is broadened due to the interstititial Pb ions. In addition, three of the glasses have a shoulder in the attenuation against temperature curves at approximately 100 K which is particularly noticeable at high frequency (Fig. 11). The evidence of a shoulder in the fourth glass (Corning 8875) is very slight. The comparison of the temperature of the shoulder with the peak observed in RW62 glass would indicate that the shoulder is due to a subsidiary attenuation peak caused by Pb ions entering the network substitutionally in the isopaustic glasses. The virtual absence of the shoulder in Corning 8875 would indicate that the Pb ions are acting almost entirely as network modifiers in this case. The network former B_2O_3 cannot be the cause of this anomalous behaviour since both Schott UDL7 and Corning 8875 glasses have no B_2O_3. It may be that the preparation procedure for the Corning glass is significantly different from the others. Further evidence that it is the Pb ions that are important in this respect arises from the behaviour of RW26, which has no PbO, but otherwise has constituents very similar to the isopaustic glasses. However, RW26 has an attenuation peak of 50 K and no evidence of any anomalous behaviour at 100 K. In addition, the size of the attenuation in RW26 is little more than half that for the isopaustic glasses indicating that in the absence of PbO the network modifiers K_2O and Na_2O do reduce the overall attenuation by breaking the B–O–B, Si–O–Si and Si–O–B bonds and by impeding the oxygen motion.

The last glass measured here is Pilkington DBC 620603 which has no PbO at all and appreciable amounts of the network former B_2O_3 and the modifier BaO. In Fig. 12 the internal friction, Q^{-1}, is compared for SiO_2, B_2O_3, 58.5 mol% SiO_2–41.5 mol% B_2O_3 [12] and DBC 620603. Q^{-1} is defined as

$$Q^{-1} = \frac{2\alpha v}{w}, \tag{2}$$

where α is the ultrasonic attenuation at angular frequency, w, in nepers cm^{-1} and v is the velocity of the appropriate acoustic wave.

The peak height for the B_2O_3–SiO_2 glass and the Pilkington glass occur at the same temperature to within experimental error and the overall attenuation for DBC 620603 is appreciably lower than for the two-component glass. It can be concluded that the barium oxide reduces the number of acoustic absorption centres, (providing it can be assumed that there is an equal relaxation strength associated with the loss centres in both the glasses).

This finding is consistent with the conventional model for the addition of a metal oxide network modifier which produces a bond rupture such that

$$\text{A–O–A} \rightarrow \text{A–O} \overset{Ba^{3+}}{\quad} \text{O–A}. \tag{3}$$

The degree of break-down of the three-dimensional silicon–oxygen network is directly proportional to the amount of modifying metal oxide in the glass,

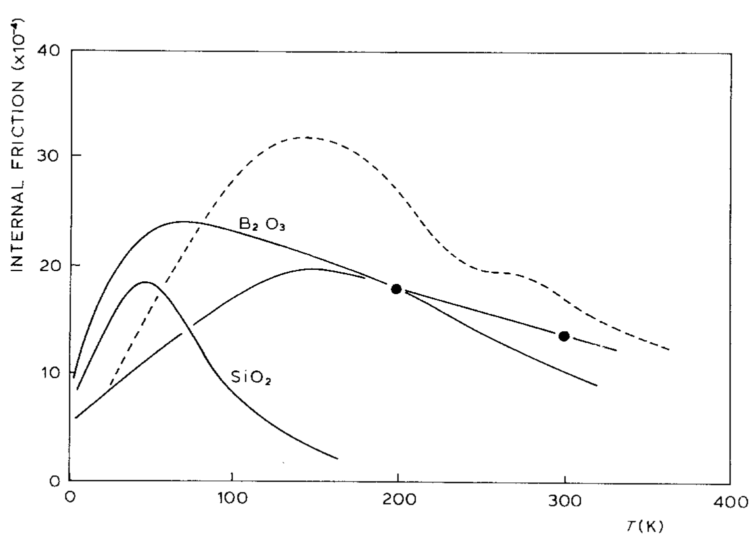

Figure 12 The temperature dependences of the internal friction for SiO_2 [4], B_2O_3 [5], 58.5 mol% SiO_2–41.5 mol% B_2O_3 [12]: - - - - -; and Pilkington DBC 620603 glass —·—.

and this is consistent with the work of Maynell *et al.* [12] who added Na_2O to the SiO_2–B_2O_3 glass and found that the attenuation decreased linearly with Na_2O concentration.

It should be noted here that the present measurements on DBC 620603 together with the work of Maynell, tend to confirm the presence of the B_2O_3 peak at approximately 100 K rather than 300 K as reported by Strakna and Savage [1].

If an acoustic attenuation peak is due to a relaxation process, as in the present case, it is usual to study its temperature dependence on frequency and so to find the activation energies of the processes responsible. It can be seen from Figs 2 to 7 that there are comparatively small shifts in peak temperature with frequency of the isopaustic delay-line glasses. The Corning glass has the largest shift from 45 K at 5 MHz to 50 K at 35 MHz. Of the non-isopaustic glasses only the DBC 620603 has a significant shift, from 135 K at 10 MHz to 155 K at 50 MHz. These shifts are of the same order of magnitude as other inorganic glasses [1, 4, 5, 12]. Because of the complicated compositions of the present glasses, the small frequency shifts observed and the assumptions implicit in the theory, it was decided that an analysis of the activation energies for the various glasses were not warranted.

One would expect a relaxation in elastic moduli to accompany the attenuation peak. However, none of the acoustic shear-wave velocities in Fig. 10 exhibit a minimum at temperatures corresponding to the attenuation peaks, although there is evidence for increases in the temperature dependence of the velocity as temperature decreases. These velocities should be corrected for thermal expansion of the samples and measurements to this end are in progress.

5. Conclusions

The temperature and frequency dependences of a range of commercial glasses have been measured with particular emphasis on the PbO–SiO_2 glasses. All the glasses exhibit a broad low-temperature attenuation peak that is consistent with an absorption mechanism caused by transverse vibrations of the oxygen atoms in the silica networks. A glass with 50 mol % SiO_2 and 50 mol % PbO (Pilkingtons RW62) has a resonance peak at 100 K, probably associated with the lead ions entering the chains substitutionally and markedly effecting the Si–O–Si bonds that produce an attenuation peak at 50 K. The four isopaustic delay-line glasses with less than 20 mol % PbO exhibit only small anomalies at 100 K with the main peak still located at 50 K. It is argued that this is due to only a fraction of the PbO entering the SiO_2 network substitutionally while the major portion acts interstitially as a network modifier. This is supported by the results of RW26 which has no PbO and no anomaly at 100 K. Finally, a glass with 45 mol % SiO_2, 21 mol % B_2O_3 and 29 mol % BaO (Pilkington DBC 620603) has behaviour consistent with bridging oxygen relaxation in a mixed SiO_2–B_2O_3 network with the overall attenuation decreased by the addition of the network modifier BaO.

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