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A mechanism for ageing in a deeply supercooled molecular glass

The temporal decay of spontaneous polarization in a molecular film is coupled with spin-polarised neutron scattering measurements to identify the ageing pathways for a deeply supercooled glassy solid. (Image credit: Oak Ridge National Laboratory/Jill Hemman).

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A mechanism for ageing in a deeply supercooled molecular glass†

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Measurements of the decay of electric fields, formed spontaneously within vapour-deposited films of cis-methyl formate, provide the first direct assessment of the energy barrier to secondary relaxation in a molecular glass. At temperatures far below the glass transition temperature, the mechanism of relaxation is shown to be through hindered molecular rotation. Magnetically-polarised neutron scattering experiments exclude diffusion, which is demonstrated to take place only close to the glass transition temperature.

Aging or relaxation in supercooled materials may be a two component process in polymeric films,1,2 metallic glasses3–6 liquid crystals7 and, as here, molecular glasses. When heated close to the glass transition temperature, Tg, the two processes, termed the primary and secondary relaxations, merge but in deeply supercooled materials they separate out with different rates and different temperature dependencies. Here, we use measurements of spontaneous dipole orientation in polarised, deeply supercooled molecular solids to follow both processes across a wide temperature range, from 0.5 Tg to Tg. We observe that the energy barrier for the secondary process drops as the growth temperature of the material is decreased.

The growth of glassy molecular solids by condensation of gas is the main growth mechanism for molecular solids in the interstellar medium,8 is frequently used for the production of molecular electronic components9 and, increasingly, for drug delivery solutions.10 It has recently been discovered that molecular ordering can occur in films formed through physical vapour deposition.11–14 The phenomenon appears to be a general consequence of the growth of thin films of molecular materials from the vapour phase. It has been established that a class of polar molecules can condense and harbour spontaneously-generated electric fields via molecular dipolar-orientation.11,12,15 Such fields are created with no external agency, such as an applied field, but are a natural consequence of deposition of a polar molecule. This so-called ‘spontelectric effect’ relies on molecular orientation and arises in the absence of any free charge.11 Since electric fields arise from collective dipole orientation, migration of dipoles, away from this ordered state, results in depolarisation. Thus, any observed decay of the field tracks molecular rotation. Accordingly, molecular rotations are followed here through the temporal decay of the spontelectric field in films of cis-methyl formate, henceforth MF. This is an extremely sensitive means of detecting molecular rotation in solids. Changes of a few hundredths of a degree in average angle of dipole orientation with time are readily observable, allowing for investigations on short timescales of a few hours.

Fig. 1 shows that the spontelectric phenomenon gives a new and highly sensitive handle on molecular rotation in polarised glasses, at deeply supercooled temperatures, where secondary relaxation is active.16 The strength of the electric field harvested by a film of MF was inferred from the surface potential measured at the film-vacuum interface atop a film of a known thickness.17 Throughout, we assume that MF adopts the cis conformation as this is energetically preferred, with a 546 meV barrier blocking transformation to trans.18 The correlation between measured electric field strength and deposition temperature, Td, for MF is shown in Fig. 1. For Td = 80 K to 89 K, Fig. 1A, field strength decreases with time, with a lag period of up to ∼2000 s before this decay begins. In this temperature regime, the internal electric field also increases with increasing Td and this has been explained elsewhere.17
Data are presented as a function of time, illustrating the rate of field decay. Data in Fig. 1A demonstrate exponential decay of the field to a constant value, \( c \), and the solid lines represent fits resulting from
\[
y(t) = y_0 \exp(-\beta t) + c,
\]
where \( t \) is the elapsed time, \( y_0 \) is the initial electric field before decay begins and \( \beta \) is the time constant for the decay process.\(^{19}\) Fits resulted in \( \beta \) values very close to 1, and we set \( \beta = 1 \) throughout. This value of \( \beta \) may be related to the short timescales over which aging is reported here.\(^{20}\) The residual surface potential measured at extended time delays in Fig. 1A, represented by the constant \( c \), is a measure of the work function of the MF film and are not related to the spontelectric effect.

In the mid-temperature regime, for \( T_d \) between 55 K and 70 K, Fig. 1B, the electric field values are constant at any given \( T_d \) and this constant value decreases as \( T_d \) increases. This is the behaviour expected of spontelectric materials.\(^{11,17}\) At low deposition temperatures, below 55 K in Fig. 1C and extending to the lowest temperature of 40 K, there is again a decay in the electric field as a function of time and, again, a lag period before electric field values start to decrease. The lag period decreases as \( T_d \) is decreased. In addition, the final value to which the field decays, variable “c” above, is lower for lower values of \( T_d \), representing residual dipole alignment. The lag periods before decay, for \( T_d \leq 55 \) K and \( T_d \geq 75 \) K are collected in Fig. 1D. For 90 K > \( T_d > 75 \) K the lag times change by an order of magnitude and decrease with increasing \( T_d \). Thus films age faster as the growth temperature is increased, as expected. Conversely, lag times for \( T_d \leq 55 \) K decrease as \( T_d \) drops lower, meaning films age faster as growth temperature drops.

**Table 1** Parameters describing the rate of field decay in films of MF

| Temperature (K) | Lag period (s) | Rate constant, \( k \) for decay of \( \langle \mu_z \rangle / \mu \), \( 10^4 \text{ s}^{-1} \) | Activation energy, \( E_{\text{act}} \) (eV) | Time constant, \( \tau \), for exp decay of \( \langle \mu_z \rangle / \mu \), \( 10^{-5} \text{ s}^{-1} \) |
|-----------------|----------------|----------------------------------------|-----------------|-----------------------------------------------|
| 40              | 2.564          | 3.900 \times 10^{-4}                  | 0.112           | 5622                                          |
| 45              | 3.348          | 2.987 \times 10^{-4}                  | 0.127           | 11 185                                        |
| 50              | 5.520          | 1.812 \times 10^{-4}                  | 0.143           | 17 230                                        |
| 55              | 8.672          | 1.153 \times 10^{-4}                  | 0.160           | 102 894                                       |
| 77.5            | 8.336          | 1.200 \times 10^{-4}                  | 0.225           | 2.35 \times 10^{-5}                           |
| 80              | 2.816          | 3.551 \times 10^{-4}                  | 0.225           | 5180                                          |
| 83              | 3.298          | 3.032 \times 10^{-4}                  | 0.234           | 5420                                          |
| 85              | 2.222          | 4.500 \times 10^{-4}                  | 0.237           | 6763                                          |
| 86.5            | 2.350          | 4.255 \times 10^{-4}                  | 0.241           | 4485                                          |
| 88              | 2.200          | 4.545 \times 10^{-4}                  | 0.245           | 5291                                          |
| 89              | 2.010          | 4.975 \times 10^{-4}                  | 0.247           | 6196                                          |
| 90.5            | 7.700          | 2.929 \times 10^{-3}                  | 0.244           | 1031                                          |

Fig. 1 Isothermal surface potential decay. (A–C) The decay in the strength of electric field measured in films of cis-\( \text{methyl formate} \) is plotted for films prepared across a range of temperatures of deposition (\( T_d \)). Measurements were performed during growth of the film, with each data point on a given curve representing a different film thickness, but data are plotted as a function of time. Data are divided into three temperature regimes: (A) high \( T_d \) where the electric field decays to a constant value irrespective of \( T_d \); lines are results from fits (see text); (B) mid-range \( T_d \) where the electric field values are stable. Lines here are added as a guide to the eye and; (C) low \( T_d \) where the electric field does not decay to zero where lines here result from fits. (D) The lag period before field decay begins, for fits presented in (A and C) are plotted as a function of \( T_d \). Systematic errors in (E) field measurements arise from systematic errors in the film thickness, ±20%.
anneal temperature for both penta-layered films, Fig. 2E, and intensities at annealing to 85 K. Above 85 K and the 120 min mark, relative films show any mixing upon growth and very little mixing after $T_d$ for a film prepared at $T_d = 45$ K and gradually annealed to higher temperatures. (B) Relative intensity for data in (A), $T_d = 45$ K; fits at specific $Q$ values were extracted and plotted as a function of time, where 0 min indicates the beginning of the first measurement. There are several time values for each annealing temperature (see main text and ESI†) and colour has been used to distinguish between annealing points. Errors arise from signal to noise limits. Lines represent fits resulting from the self-diffusion model. (C) Relative intensity at specific $Q$ values for $T_d = 65$ K. (D) Scattering length density profiles, $T_d = 45$ K; inset shows H-fraction. (E) Self-diffusion coefficients for $T_d = 45$ K and $T_d = 65$ K measured as films were annealed to progressively higher temperatures. The grey area indicates the lower limit of detection and diffusion coefficient values in this regime are too low to be modelled reliably.

isotopically labelled interfaces via diffusion, according to Fick’s Law, was fit to the reflectivity profiles. The resulting fits in Fig. 2A allow us to produce; (i) time resolved data, Fig. 2B and C, where relative intensity values have been extracted at specific $Q$ values as a function of both time and temperature for films with $T_d = 45$ K and 65 K, and (ii) a real space visualisation of the interface diffusion as scattering length density (SLD) profiles, Fig. 2D (see ESI†). High values of $Q$ are most sensitive to the layered structure of a film and changes in these values indicate mixing between layers. Neither the $T_d = 45$ K nor the $T_d = 65$ K films show any mixing upon growth and very little mixing after annealing to 85 K. Above 85 K and the 120 min mark, relative intensities at $Q = 0.151$ Å$^{-1}$ in the $T_d = 45$ K film begin to change gradually. Both $T_d = 45$ K and $T_d = 65$ K films show a step change above 90 K in $Q$ data. Above 90 K, the composite film is no longer identifiable as distinct D- and H-layers, for either the $T_d = 45$ K or the $T_d = 65$ K films; above 100 K, the MF isotopologues have completely mixed homogeneously throughout the entire film (see ESI†). This mixing results from primary structural reorganisation of the films, and demonstrates that both films have now passed the glass transition temperature. Methyl formate remains adsorbed on the substrate up to 135 K.  

Mixing for the $T_d = 45$ K film begins at a lower temperature, 90 K compared to 100 K for the $T_d = 65$ K film, indicating a lower $T_g$ and a less stable material when $T_d = 45$ K.

Self-diffusion coefficients, $D$, can be plotted as a function of anneal temperature for both penta-layered films, Fig. 2E, and trilayered films, ESI† Following growth, films have an upper limit of $D = 1 \times 10^{-20}$ cm$^2$ s$^{-1}$, the lowest diffusion coefficient that can be reliably inferred from this analysis, and there is no measureable diffusion at a resolution of 0.5 nm. Upon annealing to 85 K, $D = 4.8 \times 10^{-20}$ cm$^2$ s$^{-1}$ for $T_d = 45$ K and $6.6 \times 10^{-20}$ cm$^2$ s$^{-1}$ for $T_d = 65$ K. Thus, both systems demonstrate very small, but measureable molecular translational motions. On annealing to 100 K, the coefficient increases to $1.77 \times 10^{-15}$ cm$^2$ s$^{-1}$ for $T_d = 45$ K and $1.24 \times 10^{-15}$ cm$^2$ s$^{-1}$ for $T_d = 65$ K. Both values are representative of viscous glassy materials demonstrating liquid-like behaviour above the glass transition temperature. From 90 K and above, diffusion constants for the $T_d = 45$ K film are consistently higher than the values for the $T_d = 65$ K film, confirming the film with $T_d = 65$ K to be the more stable glass. In a separate experiment, films with $T_d = 45$ K subjected to slow thermal anneal produce a gradual reduction in surface potential as the temperature is increased, while films with $T_d = 65$ K demonstrate stable surface potentials under the same conditions; see ESI†.

Decay in the electric field for films with $T_d \leq 55$ K, Fig. 1C, is not associated with structural reorganisation caused by diffusion and therefore cannot be ascribed to the primary relaxation process. The depolarisation mechanism in MF films is directly linked to the secondary relaxation mechanism for glassy solids and electric field decay can act as a direct probe of molecular dynamics. For films of MF we see that this occurs over laboratory time scales, through molecular rotation. Films with $T_d \leq 55$ K relax via this secondary relaxation pathway, on laboratory timescales, while films with $T_d > 55$ K do not. We note that our observations are in accord with the formation of ‘ultra-stable’ glasses, as distinct from ordinary glasses. These have been observed to form if $T_d$ falls within a critical temperature window, when grown, as here, via physical vapour deposition. This window has been reported to lie between 0.8 to 0.91 $T_g$. Here we find that the critical window for ultra-stable MF glasses lies between 60 K and 75 K, that is, 0.66 $T_g$ to 0.83 $T_g$ given $T_g = 90$ K.

These real-time measurements of molecular motions are complimentary to other measurements of relaxation, such as solid-state NMR or dielectric spectroscopies, that rely on interpretation of data in the frequency domain. Solid-state NMR spectroscopy has revealed that molecular mobility may originate from collective oscillations of individual molecules within
a tightly confined volume, with energy barriers limiting the degree of oscillation possible.25,26 Such motions may not always be evident from dielectric spectroscopy measurements, leading to some confusion in the literature about the generality of the secondary relaxation pathway for species which form molecular glasses.26 Other measurements of dipole ordering via ellipsometry or X-ray scattering, for example, have not been used to probe secondary relaxations.12,27

The spontaneous effect offers a new and very sensitive means of studying relaxation phenomena in glasses far below the glass transition temperature. In a separate paper, a mean field model of the spontaneous effect is used to consider the energetics of the molecular rotations presented here. Neutron scattering data, allow us to exclude diffusion in this temperature regime. Recent work with metallic glasses has suggested that on short time scales, as reported here, it may be useful to separate out secondary relaxation processes into enthalpy and entropy changes.28 Electric field measurements, similar to those reported here, may also prove useful in studying memory effects in the rejuvenation of glasses successively annealed to different temperatures on short time scales, which have been reported for a variety of glassy materials.29,30

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Conflicts of interest

There are no conflicts to declare.

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