

## Transport Processes via Localized States in Thin *a*-Si Tunnel Barriers

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(Received 5 March 1985)

We report a model system for studying resonant tunneling in thin *a*-Si tunnel barriers. The system explores the interesting crossover regime between quantum mechanical tunneling and classical transport via localized states. Some surprising features of this process are revealed.

PACS numbers: 72.80.Ng, 73.40.Gk, 73.40.Sx

Transport via localized states is a process central to many current questions in electronic transport in solids. These include transport in amorphous semiconductors,<sup>1</sup> conduction along one-dimensional metal-oxide-semiconductor field-effect transistors,<sup>2,3</sup> and resonant tunneling through tunnel barriers<sup>4</sup> and thin insulating dielectric layers.<sup>5</sup> Broadly speaking, one believes that one understands such transport in the two limits  $L \gg l_{in}$  and  $L \ll l_{in}$ , where  $L$  is the sample length and  $l_{in}$  is the characteristic inelastic length for the material. In the first case, one has Mott variable-range hopping (VRH) where the temperature and length dependence of  $G$  go as  $\exp(-T^{-1/4})$  and  $1/L$ , respectively. In the second case, one has quantum mechanical tunneling, which is temperature independent to first order and leads to an exponential dependence on sample length.

However, there is a physically interesting regime in between, where  $L \sim l_{in}$  and in which the transport processes are poorly understood. This is the regime in which transport passes from being quantum mechanical to classical (i.e., a classical random walk). We believe that we have developed a model system based on artificial *a*-Si tunnel barriers for studying this regime experimentally. In this Letter, we describe this system and present results which clearly reveal the crossover behavior. Additionally, conductance data will be shown on tunnel junctions patterned to have submicron dimensions in which resonant tunneling through individual defects in the barrier can be resolved as sharp peaks in the differential conductance.

We have studied two basic tunnel-barrier structures, both of which are shown in the insets in Fig. 1. They differ from one another simply by the presence or absence of a conventional tunnel barrier ( $\text{SiO}_x$ ) between the base electrode and the amorphous silicon (*a*-Si). As is well known, *a*-Si has a high density of localized states in its mobility gap. In most cases the base electrode was Nb (2500 Å), electron-beam evaporated onto a sapphire substrate at 750°C, although some data are presented where an aluminum base electrode was used. In this case, the Al was deposited at ambient temperature and about 2% Si was incorporated into the film to keep the grain size small and yield a smoother film.

After the base-electrode evaporation the substrates were allowed to cool to room temperature. At this point, if it was desired to make the barrier with two oxide layers (sandwich structure) approximately 20 Å of *a*-Si were evaporated onto the surface. This was oxidized *in situ* in 2 Torr of pure oxygen for 15 h, after which the system was again evacuated and progressively thicker layers of *a*-Si deposited on top of a series of substrates. The vacuum was then broken and the films were allowed to oxidize in room air for a further 15 h. Small junction areas were defined using photoresist ( $5 \times 10^{-4} \text{ cm}^2$ ), and thin cross-strip counter electrodes of Pb were thermally evaporated to complete the devices. If, on the other hand, only the barrier with the single oxide layer was desired, the first Si deposition and subsequent *in situ* oxidation were omitted.

There was a good reason for studying both these structures. For a localized state to be in a condition of

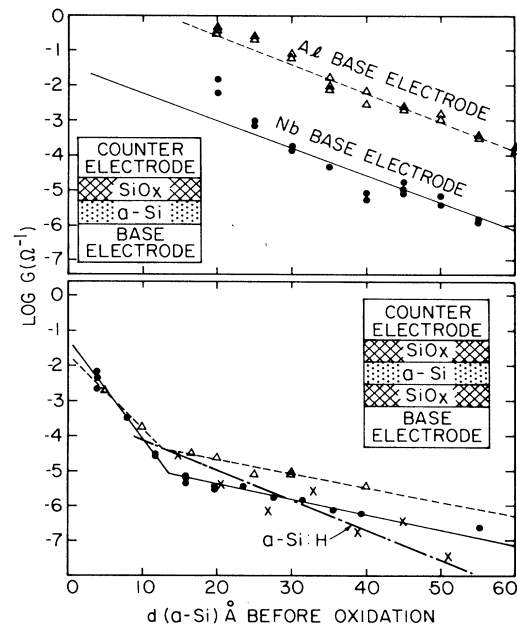


FIG. 1. Tunneling conductance as a function of *a*-Si thickness for the single-oxide (upper figure) and double-oxide (lower figure) barriers at 4.2 K.

strong resonance in a tunnel barrier it must have both its transmission coefficients to the base electrode and the counter electrode closely equal. It is clear, then, that the symmetrical sandwich structure immediately satisfies this condition, and hence is a model system for studying resonant tunneling. The condition for strong resonance will not be satisfied in the barrier with only one oxide layer until a substantial thickness of  $a$ -Si (we estimate more than 100 Å) has been deposited, and hence one would expect direct, not resonant tunneling to dominate for small  $a$ -Si thicknesses.

The extra oxide layer in the sandwich structure also has two other important advantages. First, it minimizes chemical interaction and interdiffusion with the base electrode, and second, it reduces the density of strongly hybridizing localized states immediately adjacent to the electrode, thereby minimizing any effect on the properties of the base electrode. For these reasons we believe that in the sandwich barrier we have created an ideal system for studying resonant tunneling in  $a$ -Si. While this type of structure may be new, the concept of tunneling through amorphous semiconductor barriers certainly is not, and has been studied by various workers,<sup>6-11</sup> all with rather different motivations.

Some sandwich junctions were made with hydrogen-doped  $a$ -Si ( $a$ -Si:H) in place of the pure  $a$ -Si layer, as H is known to reduce the density of localized states in  $a$ -Si. This was achieved by evaporating Si in the presence of a low-energy hydrogen-ion beam.

Because of the very high impedances of the junctions at helium temperatures and their relatively high capacitances, all electrical measurements were made at dc with a voltage source. The electronics were designed so that the effective electronic-shunt resistance across the junction was very large ( $\sim 10^{12} \Omega$ ).

Figure 1 shows conductance data at 4.2 K for a series of junctions with single (top) and double (bottom) oxide barriers and with progressively thicker  $a$ -Si layers. The junction conductance  $G = dI/dV$  was measured in each case at 4 mV, chosen so as to be above the superconducting gap structure, but still on the linear part of the  $I$ - $V$  curve. At higher voltages the  $I$ - $V$ 's become highly non-Ohmic.

Notice that for all structures the conductance is falling exponentially with  $a$ -Si thickness—the signature of quantum mechanical tunneling. The fact that the transport is via tunneling is further supported by the observation of the superconducting energy-gap structures in our  $I$ - $V$  characteristics. We do not have knowledge of the absolute  $a$ -Si and  $\text{SiO}_x$  layer thicknesses, and hence in the figure the quantity  $d$  is defined as the thickness of the second  $a$ -Si deposition in the trilayer configuration (just the first deposition in the bilayer) from timed deposition rates, before oxidation. We can, however, estimate  $d(\text{SiO}_x)$  by associat-

ing the steep section of the conductance data for  $d(a\text{-Si}) < 13 \text{ \AA}$  in the trilayer structure in Fig. 1 with oxide growth. Films of  $a$ -Si are known to double in thickness when they are oxidized,<sup>12</sup> and so this would imply that the thickness of the oxide layers is about 26 Å and the  $a$ -Si thickness is  $d - 13 \text{ \AA}$ . On comparison of the rest of the data for the two structures it is immediately obvious that the slopes differ by a factor of 2. This is exactly what one would expect if transport in the sandwich structure is by resonant tunneling [ $G \propto \exp(-ad)$ ]<sup>4,13</sup> and in the other structure by direct tunneling [ $G \propto \exp(-2ad)$ ]. Here  $1/a$  is the decay length of the wave function of the localized state. For our  $a$ -Si we find  $1/a = 11 \text{ \AA}$ .

The dashed line represents data for a sandwich structure where the  $a$ -Si was replaced by a  $a$ -Si:H to reduce the density of localized states. Notice that this appears to have the slope characteristic of direct tunneling. This is consistent with our picture if one assumes that there are no longer enough localized states in the  $a$ -Si:H for resonant tunneling to be the dominant transport mechanism.

Figure 2 shows the temperature dependence of the conductance of a series of sandwich junctions of differing  $a$ -Si thicknesses. The data in the figure are plotted as  $\log G$  vs  $T^{-1/4}$  more out of convention than on any theoretical basis, although obviously in the limit of large  $L$  one would expect to regain the Mott behavior ( $\log G \propto T^{-1/4}$ ) as seen for the 2500-Å-thick sample. [Using this result, our experimental value for  $1/a = 11 \text{ \AA}$ , and the standard Mott hopping relation we find  $N_l(0)$ , the density of localized states at the Fermi level, to be about  $1.2 \times 10^{18}$  states/eV  $\text{cm}^3$ .] For this system one can estimate  $l_{\text{in}}$  by the Mott  $R_{\text{VRH}} \sim 100 \text{ \AA}$ ; so note that the three thinnest films shown

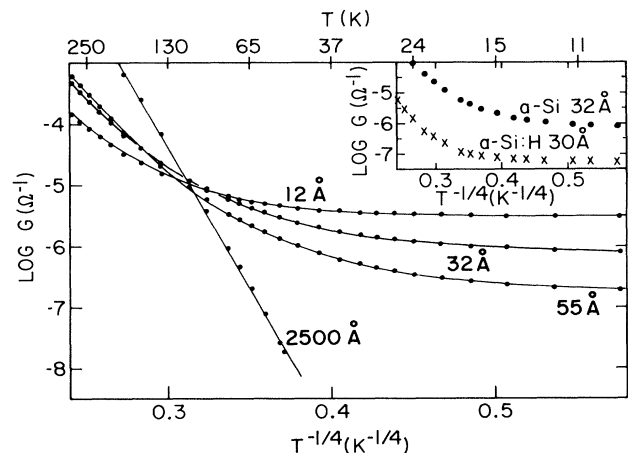


FIG. 2. Temperature dependence of the conductance of sandwich-structure barriers of increasing thickness. Inset compares one of these samples with another in which the  $a$ -Si layer was doped with hydrogen.

are all somewhat smaller than this. At high temperatures they appear to have a temperature dependence similar to that of the Mott VRH model, though the underlying physics must be different. At low temperatures the conductance is almost independent of  $T$  (leading correction  $\propto T^2$ ) and the transport is, as we have demonstrated in Fig. 1, dominated by quantum mechanical resonant tunneling. Notice that the curves actually cross at high temperatures. This point will be emphasized in Fig. 3.

In order to verify that the localized states were dominating the transport process we measured the temperature dependence of the conductance of one of our sandwich tunnel junctions containing an  $a$ -Si:H barrier. These data are shown in the inset of Fig. 2, along with a similar undoped sample for comparison. As expected, the room-temperature conductance of the H-doped sample is considerably lower (by  $\times 10$ ) and it shows a very much weaker temperature dependence throughout the whole range.

Figure 3 shows room-temperature-resistance data plotted against the logarithm of the thickness of  $a$ -Si for the series of sandwich barriers from which the three samples in Fig. 2 were selected. Notice that the resistance increases rapidly as one builds up the second oxide layer during the first 13 Å of deposited silicon. However, the really striking feature is that for thicknesses beyond this the resistance actually decreases before entering the variable-range-hopping regime ( $R \propto d$ ) for  $a$ -Si thicknesses greater than about 100 Å (see inset). Clearly coherent quantum mechanical tunneling all the way across the composite  $\text{SiO}_x/a$ -Si/ $\text{SiO}_x$  barrier is no longer taking place, or it appears that at least in part inelastic processes intervene so as to permit tunneling to take place by

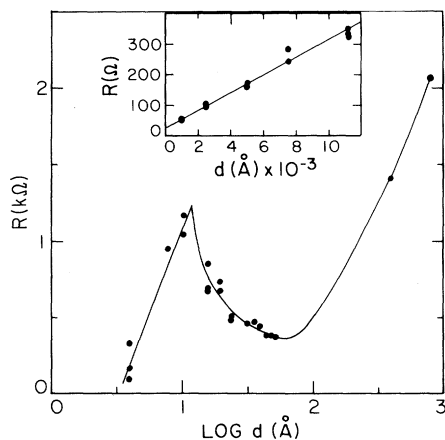


FIG. 3. Junction conductance as a function of  $a$ -Si thickness for sandwich-structure barriers at 300 K. Inset shows the behavior for much larger thicknesses. (Junction area  $= 5 \times 10^{-4} \text{ cm}^2$ .)

means of two incoherent tunneling processes through the conventional  $\text{SiO}_x$  barriers as well as by direct and resonant tunneling. Evidently the probability of such inelastic processes initially increases with barrier thickness.

This interplay between coherent and incoherent quantum mechanical processes has been the subject of several recent theoretical studies.<sup>14-16</sup> For the most part the theoretical papers focus on long ( $L \gg 1/a$ ) one-dimensional metal-oxide-semiconductor field-effect transistors. By contrast, since we estimate that the localized states in our barrier are typically hundreds of angstroms apart, our system should probably be considered an ensemble of independent, short ( $L \geq 1/a$ ), one-dimensional channels connected in parallel. Reference 14 finds that inelastic processes increase the integrated transmission of the resonant channel, while Ref. 15, by contrast, finds it essentially unchanged. In any event, on the basis of the strong temperature dependence of our junction conductances at high temperature and the peculiar behavior shown in Fig. 3, we suspect that additional inelastic processes (e.g., another channel) will be required to account for our data.

Finally, Fig. 4 is a graphic demonstration of the existence of resonant tunneling in these barrier structures, though for technical reasons it has not yet been demonstrated on our model sandwich structure. The

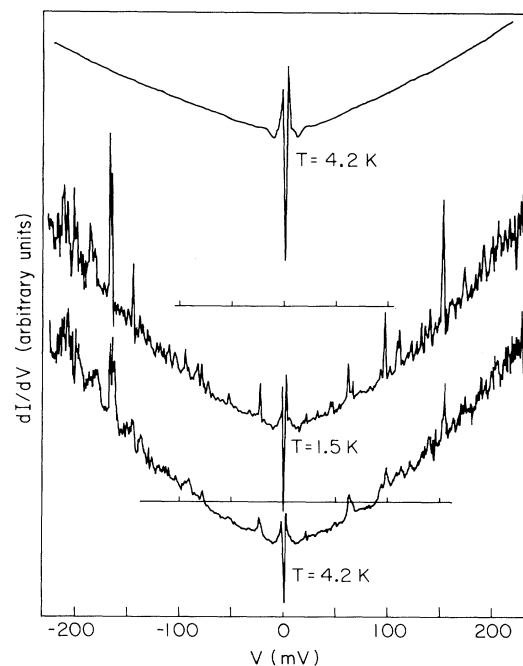


FIG. 4. Tunneling conductance as a function of bias voltage (and temperature) for 25-Å single-oxide barriers with junction areas of  $5 \times 10^{-4} \text{ cm}^2$  (upper trace) and  $5 \times 10^{-10} \text{ cm}^2$  (lower traces).

top trace is a plot of the conductance versus bias voltage for a tunnel junction with a standard-area single-oxide  $a$ -Si barrier, 25 Å thick (before oxidation) on an aluminum base electrode. Notice that, apart from the structure due to the superconducting energy gap and phonons of the lead counter electrode at low bias, it has no other interesting features. The lower trace is an otherwise identical junction except for its area, which has been patterned to be a million times smaller by projection lithography. Notice that now the data show a large number of peaks which we believe correspond to the small resonant tunneling component in the total measured current which, as we have said, is largely direct tunneling. These peaks in conductance were not resolved in the larger area junction because they were so numerous that they effectively formed a continuum. Notice, also, that the peaks grow in amplitude as the temperature is lowered from 4.2 to 1.5 K, indicating that the resonances are still being thermally broadened even though the peak width is very much greater than the Fermi-function smearing in the electrodes at these low temperatures. Measurements in a dilution refrigerator show peak heights growing down to about 0.8 K and then remaining unchanged down to below 50 mK—consistent with the idea that they arise from a coherent quantum phenomenon with an intrinsic state lifetime. Similar, but less striking evidence of thermal broadening of resonant tunneling through field-effect transistor-gate oxides has been reported by Koch and Hartstein.<sup>17</sup> We believe that what we are seeing in these traces are defects at the  $a$ -Si/SiO<sub>x</sub> interface, or perhaps in the SiO<sub>x</sub> barrier itself. Hence one should be cautious when using these results to interpret quantitatively the other data for the  $a$ -Si barriers.

This work was supported by the U. S. Office of Naval Research. The authors would also like to acknowledge useful discussions with P. A. Lee and R. A.

Street. We would also like to thank R. L. Greene for helping with the very low-temperature conductance data on the submicron junctions.

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