Direct Lifetime Measurements and Interactions of Charged Defect States in Submicron Josephson Junctions

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We have measured the emission and capture times of individual electron traps residing within the tunneling barrier of very small-area ($<0.05\ \mu\mathrm{m}^2$) Josephson junctions. The voltage-bias dependence of the times is consistent with a simple nonequilibrium model in which the bias enhances the rate for electrons to tunnel into the trap from one side of the barrier and exit out the other. Some junctions show clear evidence of interactions between traps, and for certain bias conditions the noise displays predominantly series kinetics.

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Small-area tunnel junctions have recently been the focus of a number of low-frequency noise studies.[1-4] Unlike larger systems where the low-frequency noise exhibits a rather featureless $1/f$ power spectrum, tunnel junctions can be made so small that the discrete nature of the underlying microscopic processes becomes apparent in the noise. This was first demonstrated by Rogers and Buhrman[1] who showed that the noise-power spectra of their junctions were dominated by a small number of Lorentzian features arising from the trapping and untrapping of single electrons into localized defect states within the tunneling barrier. The trapped electron alters the junction conductance by charging a small region about the trapping site, thereby blocking conduction through this channel. The voltage noise contributed by one such trap displays a series of discrete switching events, resembling a random telegraph signal, characterized by electron emission and capture times. Because the trapping couples to the junction voltage in such a simple, distinctive fashion, it is possible under certain favorable conditions to observe directly the switching behavior of one or several of these traps. In this Letter we report lifetime measurements of charged defect states in very small-area Josephson junctions under various temperature and voltage-bias conditions. The lifetimes show only a weak temperature dependence below 4 K, consistent with previous findings[2,3] that the trapping process displays tunneling kinetics at low temperatures. In contrast, the emission and capture rates are both enhanced significantly by the application of a voltage bias, regardless of polarity. We propose a simple model to explain this behavior. In addition, the noise does not always exhibit a simple superposition of random telegraph switching when several traps are active at the same time; instead, interactions between the traps can produce a voltage noise that displays series kinetics. These observations show that the low-frequency noise of this system cannot always be described by a simple parallel-kinetics model composed of independent fluctuators.

Using electron-beam lithography and a PbInAu-$\mathrm{In_2O_3}$-Pb edge-junction technology, we fabricate tunnel junctions with areas of $<0.05\ \mu\mathrm{m}^2$ having normal-state resistances on the order of 1 kΩ. When the junction is biased at voltages greater than $2\Delta/e$, charge trapping produces a voltage noise which scales with the normal resistance and the bias current. The fraction of the noise power contributed by a single trap varies inversely with junction area. Therefore, very small areas are needed to resolve individual traps, while large resistances and bias currents help overcome the measurement-system noise. Measurements are made in the temperature range 4 to 1 K where we do not expect junction-heating effects to be important. The tunneling barrier of our junctions is known to be a Schottky barrier formed at the interface of the degenerate semiconductor $\mathrm{In_2O_3}$ and the Pb counterelectrode.[5] A common defect found in these barriers is an oxygen vacancy, and it is likely that the charge trapping occurs at these sites.

When the discrete switching events due to electron trapping dominate the low-frequency noise of the junction, the real-time voltage (see Fig. 1, inset) forms a complete time record of the trapping behavior. We digitally sample the voltage and use a simple algorithm to detect and record switching events. If only one trap is active within the measurement bandwidth, a histogram of the measured emission and capture times (Fig. 1) shows exponential distributions from which the characteristic lifetimes in the charged (up) and uncharged (down) states are determined. When more than one trap is active, the histogram is piecewise exponential and the lifetimes for each trap can still be accurately deduced, provided they are not too similar.[3]

Figure 2(a) shows the temperature dependence (below 4 K) of lifetimes for a typical trap at two different bias voltages. The slow variation with temperature indicates that the transitions between the two states occur by tunneling. At higher temperatures, it is expected that the transitions will become thermally activated and the times

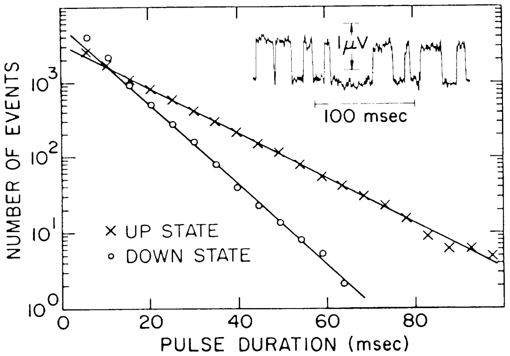

FIG. 1. Histogram of electron emission (up) and capture (down) times for a single two-state defect trap. Inset: Real-time voltage.

should then vary as $\tau \sim \exp(E_a/kT)$, where E_a is the activation energy. Note that the up time at 7 mV shows a slight increase above 2.5 K. This behavior is not often observed and we do not expect it to persist at higher temperatures. Figure 2(b) shows the temperature dependence of the quantity τ_u/τ_d (u = up state, d = down state) derived from the times in Fig. 2(a). The flattening below 2.5 K implies that the trap remains active even as the system approaches zero temperature. Above 2.5 K, the temperature is more effective in changing the duty cycle $\tau_u/(\tau_u+\tau_d)$ of the trapping. The simplest model for describing the electron-defect system is a double-well potential in which the wells represent two distinct electronic-ionic configurations; trapping and untrapping events correspond to transitions between the wells. In the thermal regime, the model predicts

$$\tau_u/\tau_d = (N_u/N_d)\exp[(E_u - E_d)/kT],$$

where N_u, N_d are the degeneracies and E_u, E_d are the energies of the two wells. Although we have insufficient high-temperature data to determine accurately the quantities N_u/N_d and $E_u - E_d$, an extrapolation of our measurements to high temperature always gives $N_u/N_d > 1$; therefore, the traps spend more time in the up (charged) state than in the down (uncharged) state as the temperature increases. This conflicts with our expectation that $N_u/N_d \to 1$ as $T \to \infty$ (the large degeneracy of conduction electrons in the electrodes should dominate both states) and suggests that a more complex model of the trap system may be required.[6,7] In particular, because of the large bias voltage, nonequilibrium effects will complicate interpretation of the temperature data.

Figure 3(a) shows the voltage-bias dependence of the

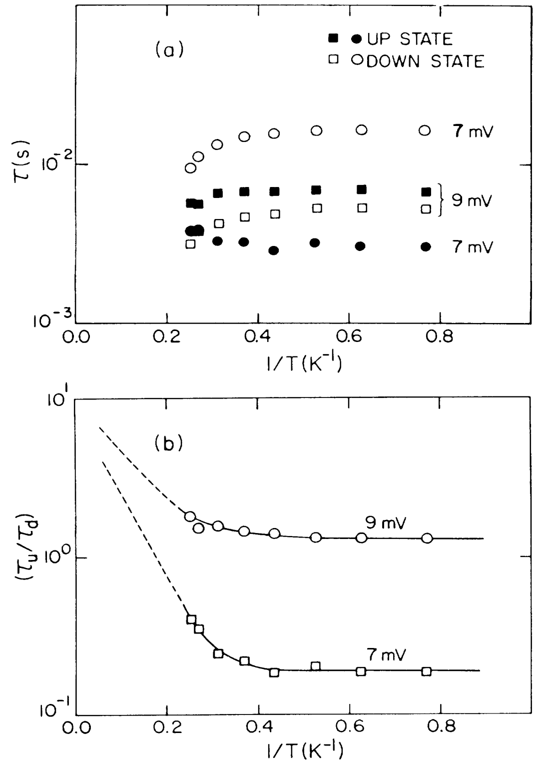

FIG. 2. (a) Temperature dependence of up- and down-state lifetimes for a typical trap at voltage biases of 7 and 9 mV. (b) Temperature dependence of τ_u/τ_d derived from data in (a).

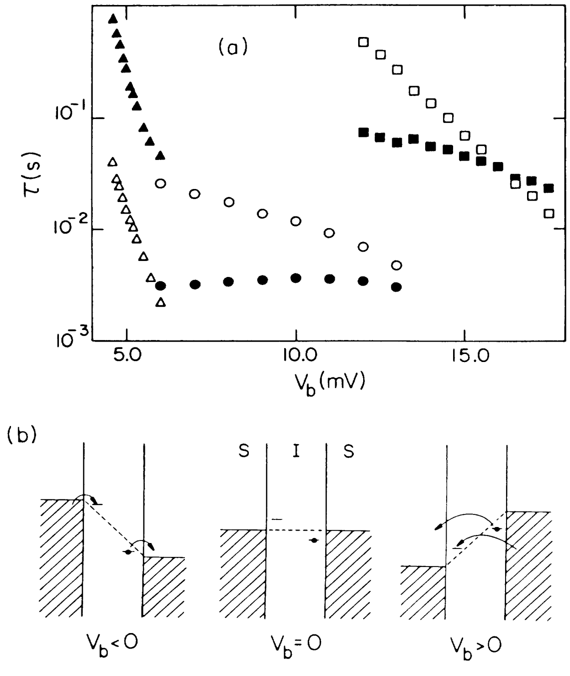

FIG. 3. (a) Voltage-bias dependence of the up (closed symbols) and down (open symbols) lifetimes for three different traps. (b) Schematic diagram of tunnel junction showing conduction electrons (shaded area) and defect traps residing within the tunneling barrier. When a bias voltage is applied, regardless of polarity, the energy level of the trap lies between the Fermi energies of the two electrodes.

lifetimes for three different traps which display a wide range of behaviors. Several general trends are noted: (1) The times are roughly exponential in the bias voltage. (2) Most often, the lifetimes decrease as the bias increases in magnitude, regardless of polarity. (3) No sharp structure is ever observed on a semilog plot; the times often show a slight curve or a small abrupt change in slope, but the bias dependence is monotonic within experimental accuracy. (4) The bias is often effective in changing the duty cycle of the trapping. (5) The strength of the bias dependence varies widely between traps, although lifetimes which increase with increasing bias typically show only a weak increase. In order to extract quantitative information from the data, it would be necessary to know in detail how the bias affects the trap. Since the times generally decrease as the magnitude of the bias increases, we propose a simple model in which the dominant effect is to shift the energy of the trap by an amount proportional to the distance of the trap from the interface [Fig. 3(b)]. When a bias is applied as in Fig. 3(b), the trap lies below the Fermi energy of the right electrode, but above the Fermi energy of the left electrode. More electrons are now available on the right to fill the trap and more holes on the left can empty the trap; hence, the emission and capture times both decrease. If the bias is reversed, the trap sees more holes on the left and more electrons to the right. The times are generally different for the two polarities, but in both cases are less than the zero-bias times. This implies that the electrons predominantly tunnel into the trap from one side of the barrier and exit out the opposite side. It is significant that both electrons and unfilled electron states are available to the trap at all temperatures; this allows the trap to remain active even at zero temperature. In contrast, Ralls *et al.*[8] observe (in metal-oxide-semiconductor field-effect transistors) a decrease in emission time and an increase in capture time as the bias is increased because the interface trap must both fill from and empty into the inversion layer. The application of a bias can increase the number of either electrons or holes available to the trap, but not both. Note that we have treated the electrodes as normal metals in Fig. 3(b), a reasonable simplification for bias voltages $V \gg 2\Delta/e$. However, the superconducting properties of the electrodes may play an important role. For example, we have evidence that the trap kinetics are altered when the trap energy level lies within the energy gap of one of the electrodes: In some instances the switching abruptly disappears below a particular bias voltage.

The data presented above were obtained by the study of individual traps, but very often several traps are active at the same time. In most cases, the resulting voltage noise shows a simple superposition of random telegraph signals. However, in some instances, more complicated behavior is observed because of interactions between the traps. Figures 4(a)–4(d) show time traces of the voltage switching in a 0.03-μm^2 junction measured at four different bias voltages. The top trace [Fig. 4(a)] shows the simple superposition of a slow trap and a much faster trap. In the second trace [Fig. 4(b)], a third voltage level appears which is much quieter than the top two levels. The third trace [Fig. 4(c)] shows perhaps the most intriguing behavior we have seen. The noise in the lower level is always quiet, while the noise in the upper level can be either quiet or noisy. However the upper level only shows transitions from the quiet state to the noisy state; it never switches from noisy to quiet as expected from detailed balance. The bottom trace [Fig. 4(d) shows very different two-level switching depending upon the state of the slow, large-amplitude switching. These remarkable observations show that the voltage bias can not only change the lifetimes of the individual traps, but can also alter the qualitative appearance of the noise by affecting the interactions between traps.

The distinct types of switching described above can be classified in terms of a hierarchy of configurational states which is organized according to the dynamical relationship between the different states of the system. The schematic diagrams on the left of Figs. 4(a)–4(d) depict our interpretation of the hierarchical relationships as deduced from the time traces. Heavy, curved lines represent discrete two-state (trapping) processes. Parallel (independent) processes are connected by thin,

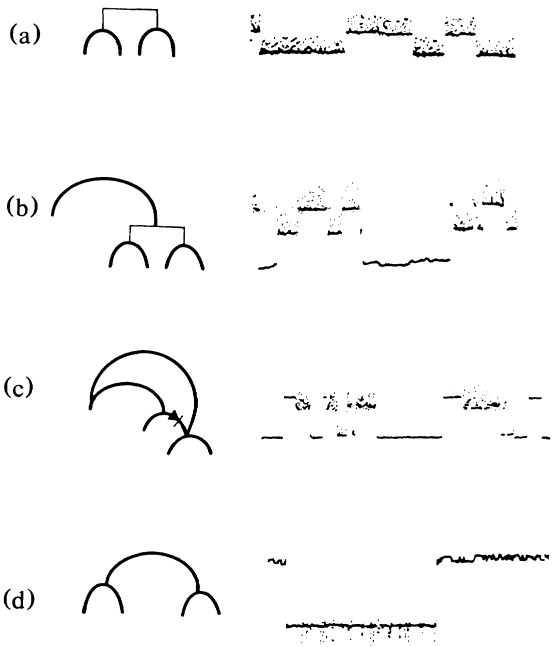

FIG. 4. Voltage switching in a 0.03-μm^2 junction at 4.2 K for four bias voltages: (a) −6 mV, (b) −10 mV, (c) −13 mV, (d) +10 mV. At left are schematic representations of the hierarchical kinetics for each time trace.

straight brackets. Series processes, which by definition are not active at the same time, are connected via another two-state process which controls which of the two traps is active. The amplitude and time scale of the switching provides a convenient means for distinguishing the different levels of the hierarchy; slow, large-amplitude switching is generally associated with the upper levels. Note that the unusual behavior in Fig. 4(c) does not fit naturally into this simple picture. The apparent violation of detailed balancing requires that one of the connections has diodelike properties; i.e., transitions occur in only one direction.

The time traces in Figs. 4(b)–4(d) provide examples of noise that exhibits series kinetics. Series or highly coupled kinetics is most often associated with systems that have scale invariance.[9] Though this is clearly not the case here, the existence of hierarchical kinetics in our junctions is not surprising. All systems exhibit interactions to some degree, but if the interactions are of short range compared to the mean fluctuator spacing, the majority of fluctuators can be assumed to be independent. In our junctions, this assumption fails because the long-range potential of the unscreened trapped charge creates an environment where interactions are likely to occur. Consequently, the noise of these ultrasmall devices can be dominated by a small number of strongly interacting traps, resulting in hierarchical fluctuation kinetics.

In conclusion, we have measured the emission and capture times of individual electron traps residing within the tunneling barrier of very small-area Josephson junctions. Below 4 K, the times vary slowly which demonstrates that the trapping kinetics is dominated by tunneling and implies that the trap remains active even at zero temperature. The voltage-bias dependence of the times is consistent with a simple model which predicts that increasing the bias enhances the rate for electrons to tunnel into the trap from one side of the barrier and exit out the opposite side. Finally, we have recorded a variety of complex interactions between traps. The interactions are affected by bias conditions and result in a voltage noise that displays series kinetics. These findings suggest that coupled kinetics may play an important role in determining the dynamic and thermodynamic properties of ultrasmall systems.

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