Light-Activated Telegraph Noise in AlGaAs Tunnel Barriers: Optical Probing of a Single Defect

P. M. Campbell, E. S. Snow, W. J. Moore, O. J. Glembocki, and S. W. Kirchoefer
Naval Research Laboratory, Washington, D.C. 20375

(Received 2 January 1991)

We observe light-activated switching between discrete resistance states in GaAs/AlGaAs single-barrier tunnel structures. This switching is caused by a change in charge state of a single hole trap which modulates the current through a small region of low barrier height generated by a crystalline dislocation propagating through the barrier. Each switching event corresponds to the capture or subsequent release of a single photogenerated hole. We are therefore able to probe this single charge trap by optically inducing changes in the occupancy of its charge states.

PACS numbers: 73.50.Td, 68.55.Ln, 73.40.−c, 78.65.Fa

There has been a recent surge of interest in the physics of structures in which the change in charge state or atomic configuration of a single defect causes a discrete change in some measurable quantity such as resistance [1-6]. Such random telegraph noise (RTN) arising from single defects should be observable only in very small devices. However, several papers have reported the observation of RTN in large samples which show evidence of arising from single defects. Judd *et al.* [7] observed RTN in ramped single-barrier diodes, with thermal activation energies close to the donor binding energy in the AlGaAs barrier. Cavicchi and Panish [8] observed RTN in transport perpendicular to single quantum wells which also suggested the action of single defects.

In a recent paper [9], we reported light-activated resistance switching in a single large-area AlGaAs tunnel device, which acted as an extraordinarily sensitive light detector. Several properties of this switching suggested that it was caused by the action of a single charge trap. To explain how single-trapping events could be observed in such a large structure, we postulated (as did Refs. [7] and [8]) the existence of small regions of high local current density where a single trap could have a large effect on the current. The evidence presented in Ref. [9] in support of this picture was indirect and based on the behavior of one device.

In this Letter we report that this light-activated switching is common in these structures, and demonstrate that it is caused by the change in charge state of a *single* hole trap located near a small region of low tunnel barrier height. Such regions are generated by a crystalline dislocation propagating through the tunnel barrier, which lowers the barrier in the vicinity of the dislocation. This low barrier allows such a high local current density that the current through this small area can far exceed the current in the rest of the device. A change in charge state of a single trap located near this region can, by modulating this localized current, produce observable switching events in large devices. This mechanism can account for the phenomena of Refs. [7] and [8]. These naturally occurring nanostructures can be used in lieu of nanometric fabrication to obtain the small dimensions needed to observe single-trap events.

The unique aspect of this switching phenomenon which distinguishes it from previous work in single-defect RTN is the optically activated nature of the switching. The fact that the transition between resistance states is controlled by the incident photon flux provides an independent variable not heretofore available in RTN. The light dependence provides direct evidence that this switching is mediated by the capture of *one* photogenerated charge by a *single* trap. We are able to optically probe this single trap by changing the occupancy of its charge states with light (independently of temperature and bias) while observing transitions between states.

The samples were grown by molecular-beam epitaxy and consist of an n^+ GaAs substrate, an n^+ GaAs buffer (1 μm thick, 2×10^{18} cm^{-3} Si doped), an n^- GaAs drift region (1 μm, 1×10^{15} cm^{-3} Si), an Al$_x$Ga$_{1-x}$As tunnel barrier (14 nm, undoped, $x=0.4$), and an n^+ GaAs emitter (1 μm, 2×10^{18} cm^{-3} Si). The samples were etched to form mesas ≈ 100 μm across. Au/Ge/Ni contacts were alloyed to the mesa tops with light-admitting windows and to the back of the substrate with a planar contact. The inset in Fig. 1(a) shows the energy-band diagram of the device under bias.

We observe two types of current-voltage characteristics in these devices: Figure 1(a) shows a representative example of each type. The "normal" devices show a current that is roughly exponential in voltage over a wide bias range, as expected for single rectangular-barrier tunnel structures [10]. The "anomalous" ones are characterized by a large additional nonexponential current term. This excess current varies from device to device and can raise the total current by several orders of magnitude.

Under constant bias, many of the anomalous (but *none* of the normal) devices exhibit discrete current fluctuations in time. For each device, the number of states, the amplitude, and the frequency of this switching vary with temperature T and bias V. Many anomalous devices show switching only when illuminated: A minority of these show two-level switching in which the occupancy of the two levels is determined by the light flux. Figure 1(b) shows a set of such switching events for the anomalous

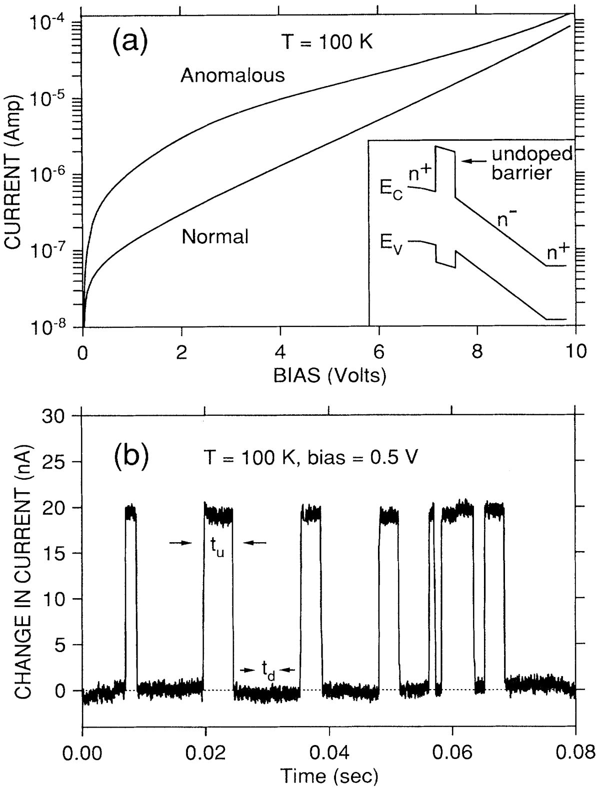

FIG. 1. (a) Current vs voltage of normal and anomalous devices. Inset: Energy-band diagram of device under bias. (b) Under illumination, the light-active anomalous device switches between two well-defined current states.

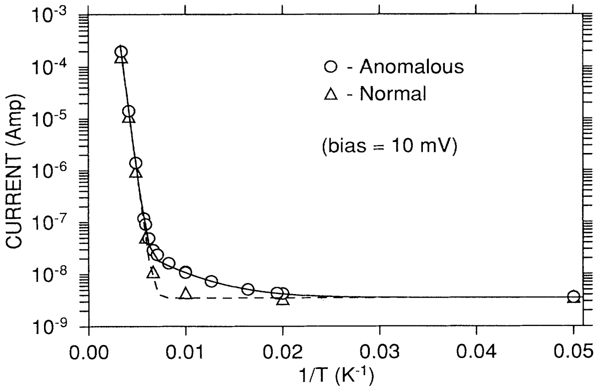

FIG. 2. Measured current vs $1/T$ of normal and anomalous devices. Solid- and dashed-line fits are defined in text.

device of Fig. 1(a). When exposed to light energy above the GaAs band gap, the current switches between two and only two states, defined here as the up (high-current) and down (low-current) states. The current step size is fixed for constant V and T. In the dark, the current is always in the down state. The sensitivity of the switching to light energy increases greatly above the GaAs band gap [9], which implies that the switching is mediated by photogenerated carriers in the n^- GaAs drift region. Since electrons are present even without light, this switching must be caused by photogenerated holes.

For fixed V and T, the measured transition rate τ_u^{-1} out of the up state in these two-state light-active devices is independent of incident light intensity. However, the transition rate τ_d^{-1} out of the down state is proportional (over many orders of magnitude) to the incident above-gap light intensity, which implies that the transition out of the down state is due to a *single-photon event.* This result, conjoined with the fact that the system switches between two and only two well-defined states, implies that *this light-activated switching is caused by the capture of a single photogenerated hole by a single hole trap.*

Photogenerated holes created in the depleted portion of the n^- GaAs drift region will accelerate back to the barrier and collect there with low probability of recombination. The capture of a hole by a trap in the AlGaAs barrier will lower the electrostatic potential and thus enhance the tunneling of electrons through the barrier in the vicinity of the trap, producing a sudden increase in the current as observed. However, calculations have shown that the effect of a single charge on a trap in a uniform tunnel barrier would be far too small to observe in the large structures used here [11]. Only if a large fraction of the total current flowed through a small region of the barrier would the trapping of a charge near this region cause an observable change in current.

Several independent experimental facts support the existence of small current paths through the tunnel barrier. We have already noted that the anomalous devices differ from the normal ones by a large excess current, and that only the anomalous devices show RTN. This suggests that the anomalous devices possess an additional current mechanism other than the normal barrier tunneling. Also, many anomalous (but no normal) devices show pinpoint light emission when biased above the threshold voltage for impact ionization. Such pinpoint emission is correlated with local high-current regions [12,13].

Additional evidence for the existence of localized high-current regions in the anomalous devices comes from thermal activation data. Figure 2 shows a graph of current I vs $1/T$ for the anomalous (also light-active) and normal devices of Fig. 1(a). Both are dominated at low temperature by a constant-tunneling current and at high temperature by thermionic emission over the barrier. A fit of I/T^2 vs $1/T$ at high T yields an effective tunnel barrier height of 245 ± 5 meV, which is the difference between the conduction-band offset ΔE_c of the AlGaAs barrier and the Fermi level E_F of the n^+ GaAs emitter [14]. This value agrees with that expected for an $\mathrm{Al_{0.38}Ga_{0.62}As}$ barrier with $\Delta E_c = 325$ meV [15] (assuming $\Delta E_c{:}\Delta E_v = 70\%{:}30\%$) and $E_F = 80$ meV [16] for the GaAs emitter. The dashed line in Fig. 2 is a sum of the constant-tunneling term and the thermionic-emission term and provides an excellent fit to the normal-device current. The anomalous-device current deviates from this fit in the intermediate $1/T$ range, but agrees if a second thermionic-emission term with a barrier height of 12 ± 3 meV is added to the fit, yielding the solid line. This result implies that part of the anomalous device has a much lower barrier.

A rough idea of the size of this low-barrier region can be obtained from the ratio of the intercepts of the two thermionic-emission terms, which should scale as the areas of the two regions since in this limit the barrier heights are insignificant. In Fig. 2 this ratio gives a low-barrier region $\approx 10^{-8}$ times the device area, equivalent to a circular region approximately 10 nm in diameter. Almost all anomalous (but no normal) devices show such low-barrier behavior in thermal activation, with most measured low barriers falling between 10 and 40 meV and estimated diameters between 3 and 40 nm.

Such activated behavior is also evident in the $1/T$ dependence of the switching. Figure 3 plots τ_u^{-1} and τ_d^{-1} vs $1/T$, measured under constant V and incident light flux, for one particular two-level light-active device (the anomalous device of Figs. 1 and 2) [17]. The $1/T$ dependence of τ_u^{-1}, the transition rate out of the up state, is very similar to that of the current in this device (see Fig. 2). A two-barrier fit using the barrier heights obtained from Fig. 2 produces the solid line in Fig. 3. However, there is no *a priori* reason to expect τ_u^{-1} to bear any relation to the current. This correlation and measurements which show that τ_u^{-1} varies linearly with I at constant T imply that the transition out of the up state in this device depends on the electron current. This would be so if the hole trap returns to the down state by capturing an electron traversing the barrier rather than by emitting the hole back to the valence band. The dominant role of the full barrier in the high-T behavior of τ_u^{-1} suggests that the active trap in this device is located in the large barrier but near enough to the low barrier to interact with the low-barrier current. If the trap were in the low-barrier region, the low barrier should dominate here.

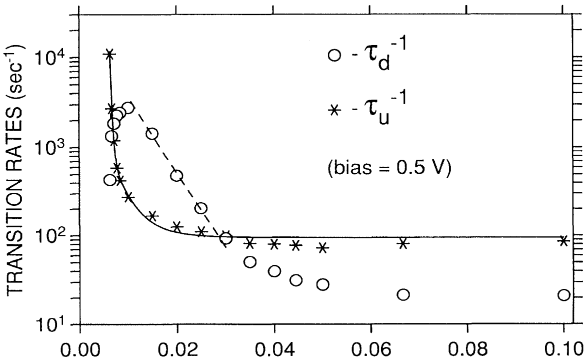

FIG. 3. Measured transition rates τ^{-1} out of the up and down states vs $1/T$ for one particular two-level light-active device. Solid and dashed lines are defined in text.

The transition rate out of the down state, τ_d^{-1}, has a constant low-temperature regime and a thermally activated regime (dashed line in Fig. 3) with activation energy 17 ± 2 meV. This indicates a low barrier to hole capture, whose origin is discussed below. At high T, as the current becomes dominated by thermionic emission, τ_d^{-1} deviates from this activated behavior and decreases sharply. Treating this decrease as arising from thermionic emission gives a barrier height of 259 meV, in reasonable agreement with the effective electron barrier height obtained from Fig. 2. The photogenerated holes accumulating at the AlGaAs barrier prior to capture by the trap can recombine with the electrons traversing the barrier. Thus, the onset of thermionic emission will reduce the number of holes available for capture, and the transition rate τ_d^{-1} will decrease at the same rate as the current increases, as observed in this device.

All of the major experimental facts described above can be explained by a model in which this small region of low barrier height is generated by the strain field of a crystalline dislocation. We observe excess current as in Fig. 1(a) in many types of structures, including thick samples with many barriers, which requires an extended current path in the growth direction through all barriers. Such a path can be created by a dislocation such as a line defect propagating up from the substrate and passing through the barriers. The density of excess current paths in our samples is ≈ 1 per device, in agreement with the substrate dislocation density of 10^4 cm^{-2}. Cavicchi and Panish [8] noted this correlation in their samples, and suggested threading dislocations as a cause of filamentary current paths out of their quantum wells.

A line defect creates a strain field arising from the volume dilation $\Delta v/v$ in the distorted region of the crystal. The strain-induced energy change in each band can be calculated from $\Delta E = \epsilon(\Delta v/v)$ if the hydrostatic deformation potential $\epsilon = dE/d\ln v$ and $\Delta v/v$ are known. We use $\epsilon_c = -15$ eV and $\epsilon_v = -8$ eV for the conduction and valence bands of $Al_{0.4}Ga_{0.6}As$ [15,18]. Taking the functional form for the spatial dependence of $\Delta v/v$ for a line defect [19] and assuming a perpendicular displacement of one lattice constant (i.e., an edge dislocation), the conduction band of the strained AlGaAs is lowered relative to the unstrained material by an amount that varies with position relative to the dislocation. We calculate a conduction-band lowering $\geq \Delta E_c$ (the conduction-band offset) within a cylinder of diameter 3 nm parallel to the line defect. The effective barrier height within this region will be dramatically reduced [20], in agreement with our experimental findings of low barrier heights of 10–40 meV within small regions with estimated diameters of 3–40 nm. The reduced barrier height we measure is some average value over the area of the strain field. The actual dislocations may in fact be more complex than the simple edge dislocation used in the above calculation, which would alter the geometry of the strain field. Despite such details, the simple calculations above show that dislocations can lower barrier heights by the amounts, in regions roughly the size, necessary to explain all our major results [21].

The capture of a single charge by a trap in the barrier can induce a large modulation of the current [11] through an area the size of the barrier-lowered region. If the excess current through this region comprises a large fraction of the total current through the device, as in this case, then the modulation induced by this single trap will be observable. We measure current modulations of a few percent, well within the range predicted by Ref. [10]. The size of this modulation in a given device depends upon the location of the trap relative to the low-barrier region. The electrical, optical, and thermal properties of this modulation depend upon the identify of the controlling charge trap. The structure of the dislocation determines the properties of the strain field and hence of the low-barrier region, which determines the amount of excess current through this region. These variables are random in our structures, so that one sees large variations in the measured properties. Average current densities through these low-barrier regions were in the 10^6–10^7-A/cm^2 range for this work. Current densities in excess of 10^9 A/cm^2 did not degrade the light-activated switching, in agreement with the high-current densities achieved in fabricated nanoconstrictions exhibiting stable RTN [5].

In summary, the light dependence of this optically activated RTN provides direct evidence that this process is mediated by a change in charge state of a single hole trap. This trap modulates the current through a small region of low-barrier height generated by the strain field of a line defect propagating through the barrier. These dislocation-induced current paths offer a naturally occurring alternative to nanolithographically fabricated devices for the study of single-defect phenomena. These devices, some of which show extraordinary light sensitivity [9], rely on the fortuitous location of a trap in the vicinity of a dislocation passing through the barrier. The controlled fabrication of such structures would allow the creation of a new class of optical devices based on the action of a single charge trap.

---

[1] K. S. Ralls *et al.*, Phys. Rev. Lett. **52**, 228 (1984).
[2] C. T. Rogers and R. A. Buhrman, Phys. Rev. Lett. **55**, 859 (1985).
[3] K. R. Farmer, C. T. Rogers, and R. A. Buhrman, Phys. Rev. Lett. **58**, 2255 (1987).
[4] W. T. Wakai and D. J. Van Harlingen, Phys. Rev. Lett. **58**, 1687 (1987).
[5] K. S. Ralls and R. A. Buhrman, Phys. Rev. Lett. **60**, 2434 (1988).
[6] Xiuguang Jiang and J. C. Garland, Phys. Rev. Lett. **66**, 496 (1991).
[7] T. Judd *et al.*, Appl. Phys. Lett. **49**, 1652 (1986).
[8] R. E. Cavicchi and M. B. Panish, J. Appl. Phys. **67**, 873 (1990).
[9] E. S. Snow, P. M. Campbell, O. J. Glembocki, W. J. Moore, and S. W. Kirchoefer, Appl. Phys. Lett. **56**, 117 (1990).
[10] C. B. Duke, *Tunneling in Solids* (Academic, New York, 1969).
[11] Fred W. Schmidlin, J. Appl. Phys. **37**, 2823 (1966).
[12] A. G. Chynoweth and G. L. Pearson, J. Appl. Phys. **29**, 1103 (1958).
[13] E. S. Snow, S. W. Kirchoefer, P. M. Campbell, and O. J. Glembocki, Appl. Phys. Lett. **54**, 2124 (1989).
[14] J. Batey and S. L. Wright, J. Appl. Phys. **59**, 200 (1986).
[15] Sadao Adachi, J. Appl. Phys. **58**, R1 (1985).
[16] W. B. Joyce and R. W. Dixon, Appl. Phys. Lett. **31**, 354 (1977).
[17] Unlike the results of Fig. 2, in which virtually all anomalous devices show similar behavior, there is wide variation among devices in transition-rate behavior. While the results derived from the data of Fig. 3 are valid only for this one device, they illustrate the type of detailed information that can be obtained from such analysis.
[18] J. A. Verges, D. Glotzel, M. Cardona, and O. K. Anderson, Phys. Status Solidi (b) **113**, 519 (1982).
[19] S. S. Kulin, A. D. Kulin, and A. D. Kurtz, Acta Metall. **2**, 354 (1954).
[20] The GaAs band structure is similarly affected by the strain field. However, the relevant barrier is the height of the strained AlGaAs conduction-band edge above the Fermi level of the n^+ emitter. The Fermi level is constant in both strained and unstrained materials throughout the structure. Therefore, the strain lowers the AlGaAs band edge toward the Fermi level, thus reducing the barrier height. A precise calculation of this effective barrier height should include the effect of charge distribution self-consistently.
[21] Within this 3-nm-diam strained region defined above, the calculated valence-band offset likewise decreases from its unstrained value to ≈ 0, which may explain the origin of the low barrier to hole capture of 17 ± 2 meV measured from τ_d^{-1} in Fig. 3. The fact that the temperature dependence of τ_d^{-1} is dominated by this low barrier to hole capture suggests that in this particular device the hole passes through the low-hole-barrier region prior to capture by the trap. Such a funneling of holes through this region would greatly increase their chances of capture by the hole trap, which may explain why some of these devices (including the one shown in Fig. 3) are such efficient light detectors.