PHOTOSENSITIVE IMPURITY-ASSISTED TUNNELING (Au, 77°K) IN GaAs TUNNEL DIODES*

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(Received 19 January 1970)

A photostimulated channel for tunneling in GaAs tunnel diodes is described and identified with the presence of Au impurities on the *n* side of the space-charge region. The mechanism for the impurity-assisted tunneling is identified with an inelastic excitation of the electronic states associated with the Au impurities.

One of the major trends in modern tunneling spectroscopy is its development as a means of probing various features of the junction region of a tunnel junction.[1] Both photosensitive[2] and impurity-assisted[3] tunneling in semiconductors have received renewed interest almost a decade following their initial discovery.[4-6] In this Letter we report the observation of an impurity-assisted tunneling mode caused by the reversible quasistable excitation of the (Au) impurity either by band-gap radiation or by large injection current. A line-shape analysis leads us to identify this mode as the inelastic excitation of an electronic state of the Au impurity by the tunneling electron. In contrast to previous work,[2,5] this experiment probes the excitation spectrum of the impurity itself, rather than modifications in the shape of the space-charge potential caused by alterations of the charge state of the impurity.

The GaAs tunnel junctions of the present study are fabricated by alloying either Au-Ge eutectic or Au-Sb eutectic, doped with Ge, on *p*-type substrate crystals of doping $\geq 10^{19}/\mathrm{cm}^3$. These alloys melt, readily wet, and dissolve a portion of the substrate crystal at temperatures considerably below 700°C. As either alloy system is cooled after being melted on the substrate, some of the GaAs that is dissolved in the Au alloy regrows degenerate *n* type (Ge doped) on the *p*-type parent crystal, and with also a considerable Au concentration in the regrown region. Although the Au concentration in the regrown region has not been determined, the process of transient growth (<1 min) of GaAs from a Au solution will result in a concentration as high as $\sim 10^{17}/\mathrm{cm}^3$.[5,7]

The basic experimental phenomenon that we wish to report is illustrated in Fig. 1, which shows data taken on a tunnel diode fabricated by alloying Au-Sb + 2% Ge on GaAs:Zn. To obtain the data shown in the figure, we cool the diode at zero bias to 77°K and then apply bias. If relatively low biases (<0.5 V) are not exceeded, the lower curve is obtained and may be retraced repeatedly. If carrier injection (i.e., excitation) occurs, either electrical by application of sufficient voltage, or by shining on the device light of band-gap or higher energy, the current in the negative-resistance region of the tunnel diode (0.15 to ~0.5 V) is increased as shown. The photoinduced current shown in Fig. 1 is not obtained unless a Au-rich alloy is used to produce the *n*-type side of the tunnel diode.

If the diode temperature is maintained at 77°K and the light or electrical excitation is removed,

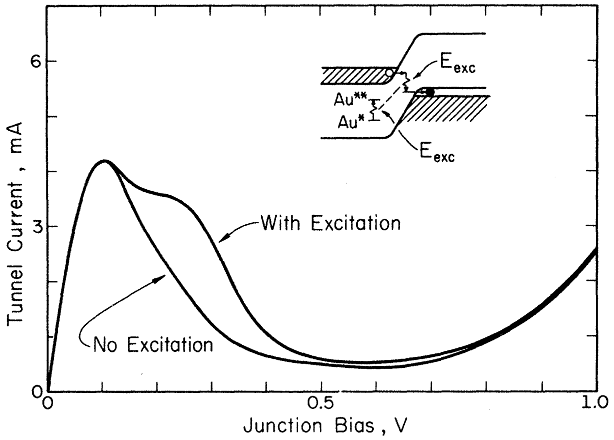

FIG. 1. *I-V* characteristics of a GaAs tunnel diode at 77°K formed by alloying Ge-doped Au-Sb eutectic on GaAs:Zn. The lower curve, labeled "no excitation," shows the characteristic obtained by sweeping the bias from 0 to 1 V. The upper characteristic is obtained upon shining band-gap or higher energy radiation upon the diode. The inset illustrates the mechanism thought to be responsible for the enhancement of the current.

the altered characteristic may not decay completely to the unexcited case for over 1 hour. This indicates that the electrical or optical injection process that alters the ground state of the Au trap (located on the *n*-type side of the junction transition) produces long-lived changes which create quasistable Au levels that are active in tunneling and that are not otherwise available. In the present work we do not attempt to determine the properties of the ground state of the Au trap and are concerned only with tunneling involving the quasistable Au states. These states, although they may affect excess carrier lifetime, do not affect the diode recombination radiation. Therefore, we conclude that the tunnel effects of interest here are due to Au on the *n*-type side of the junction and not on the *p*-type side where they would tend to diminish band-to-band recombination and the radiation output that we detect at high values of the bias.

That the Au trap is involved in tunneling is clear from the junction fabrication technique resulting in the data of Fig. 1. For the diode of Fig. 1, even in the unexcited condition some impurity-assisted (excess) current is evident in the bias range 0.15-0.30 V. This fact makes it difficult to attempt a theoretical fit to the experimental data of Fig. 1. For this reason, the diode of Fig. 2, which has less impurity-assisted tunneling in the unexcited case (not shown), is used for comparison of experimental data with theoretical predictions. For completeness we mention that still another experimental finding indicates the role of impurity-assisted tunneling; that is, a large excess noise is measured in the same bias range that the impurity-assisted tunneling current is large.[6]

The occurrence of photoinduced quasistable, nonequilibrium charge states of impurities in tunnel junctions is a familiar one.[2,5] We schematically represent the creation of such a state, labeled by Au*, as

$$\mathrm{Au}+h\nu \rightarrow \mathrm{Au}^{*}+q, \qquad (1)$$

where the liberated charge q may or may not be localized. Two features distinguish the data shown in Figs. 1 and 2 from previous observations. First, the invariance of the leading edge of the I-V characteristic under the excitation of the impurity shows that unlike previous observations of photosensitive tunneling,[2,5] the dominant mechanism for the photosensitivity is <u>not</u> a change in the space-charge potential induced by the change in the charge state of the impurity. Second, the occurrence of the extra current in the tunneling region of the I-V characteristic distinguishes it from the "usual" excess-current channels in p-n diodes.[4,6,8] Consequently, we conclude that this extra current is tunneling current assisted by the Au trap in the junction.

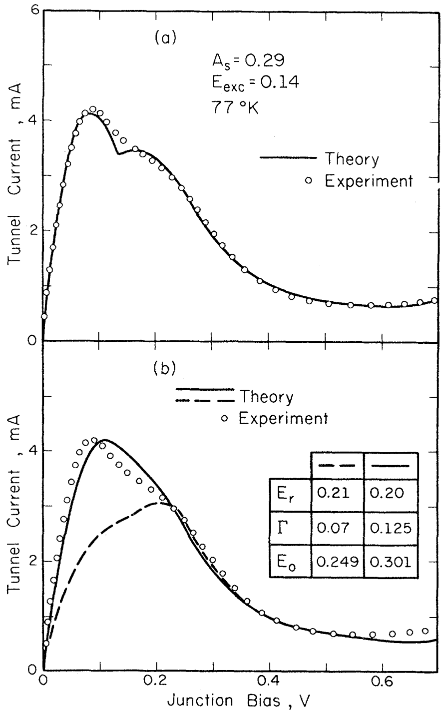

FIG. 2. Comparison of the experimentally measured enhanced I-V characteristics with the theoretical predictions for (a) inelastic tunneling, and (b) resonant elastic tunneling. The diode is fabricated by alloying Au-Ge eutectic on p-type GaAs:Ge. The theoretical characteristic in (a) was obtained from Eq. (3) in the text using the parameters indicated. The theoretical characteristics in (b) were obtained from Eq. (2) in the text and the parameters shown in the figure.

Two mechanisms can be responsible for such impurity-assisted tunneling: resonant elastic tunneling[1,9,10] or inelastic tunneling.[1,11,14] The resonant tunneling can occur via either the ground or excited states of the quasistable Au* impurity. A calculation of the current using the uniform-field model[4] for the barrier-penetration factor leads to the approximate result

$$I_r(eV) \cong I_0(eV)\left[\frac{E_0}{eV}\right]\left[\tan^{-1}\left(\frac{E_r}{\Gamma}\right)-\tan^{-1}\left(\frac{E_r-eV}{\Gamma}\right)\right] \qquad (2)$$

for a resonant state on the n side of the junction of width Γ and energy E_r below the Fermi energy. We use I_0 to denote the tunneling current in the absence of the impurity states, and E_0 to denote an appropriate scale factor. The poor description of the data afforded by Eq. (2) is shown in Fig. 2(b). In addition, the energy of these resonant states depends on their position in the junction. Therefore a more complete theoretical characteristic would predict a resonance structure even more smeared out than that in Fig. 2(b).

These difficulties with the resonant-tunneling hypothesis suggest that the mechansim for the extra current flow channel is inelastic tunneling. The line shape associated with this mechanism is given by[14]

$$I_t(eV)=I_0(eV)+A_sI_0(eV-E_{\rm exc})\theta(eV-E_{\rm exc}). \quad (3)$$

Comparison of this line shape to the experimental data is shown in Fig. 2(a). The inelastic tunneling process is represented schematically as

$$e_L+\mathrm{Au}^*\rightarrow e_R'+\mathrm{Au}^{**}, \quad (4)$$

for a left (L) to right (R) transition with the energy loss $E_{\rm exc}$ given by the tunneling to the impurity. A sharp threshold is anticipated because $E_{\rm exc}$ should be rather insensitive to the position of the impurity.[1] The value of the excitation energy, $E_{\rm exc}=150\pm10$ meV, suggests strongly an electronic excitation of the Au impurity (as opposed, e.g., to a local vibronic excitation). In this context, it is worth noting that this energy is the same in every diode we have fabricated in which the effect is observed. Thus it does not depend on the details of the space-charge region, the electrode doping, or the fine details (within energies ~meV) of the electronic environment of the impurity.

Summarizing: We have observed a new phenomenon, photosensitized impurity-assisted tunneling, and identified it with the presence of Au impurities in the junction. The features of this assisted tunneling are consistent with the hypothesis that it is an inelastic impurity-excitation process with excitation energy $E_{\rm exc}=150\pm10$ meV. They are inconsistent with the hypotheses of space-charge effects and resonant-elastic tunneling.

For technical assistance we thank A. M. Andrews, P. D. Dapkus, T. H. Demetrakopoulos, G. Studley Morris, and V. Swanson.

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*Work supported by Advanced Research Projects Agency Contract No. SD-131.

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