TUNNELING IN III-V COMPOUND p-n JUNCTIONS

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(Received 17 May 1965)

Measurements near 1°K on the bell-shaped resistance-voltage region[1-3] around zero bias in GaP, InP, and GaAs tunnel p-n junctions have revealed previously unobserved effects. Changes in incremental resistance as large as 1180% have been observed in alloy InP junctions. The magnitude of the effect depends upon the impurity concentration on both sides of the junction. Our studies are confined to lightly doped tunnel junctions. The data being reported come from a population of over 250 diodes. More accurate data on the temperature dependence of the zero bias resistance have been obtained. Previous observations of these effects have all been on alloy junctions, but we have also found them in diffused diodes (GaAs), indicating that these phenomena are not associated with a particular junction fabrication technique. The effects are independent of the method of preparation and depend only on the specific semiconductor. Highly symmetric curves have been observed in GaP and InP because of the constant background resistance, thus making a voltage-dependence analysis possible. Experimental evidence will be presented which indicates that at least three separate effects have been observed which lead to bell-shaped resistance-voltage curves. Previous attempts at explanation have been in terms of only one anomaly. Spike structure similar to that reported in the Pb salts[4] has also been seen.

The GaP and InP junctions were made by alloying either Sn-S or Sn-Te dots into p-type wafers doped with either zinc or cadmium, while the diffused GaAs junctions were prepared by zinc duffusion into n-type material doped with either selenium, sulphur, or tellurium.[5] Various precautions, such as the use of very large area contacts, were taken to eliminate effects from the metal-semiconductor end contacts. The junctions were immersed in liquid helium which could be pumped to near 1°K. Measurements of the temperature variation of the zero-bias resistance were carried out under quasistatic conditions by allowing the bath to slowly decay back to 4.2°K. The decay rate ($\Delta T/\Delta t$) was approximately 0.016°K/min. This technique made possible the taking of a high density of data points during one run. The static-temperature approach used in earlier experiments[2,3] requires multiple runs which yield much less information. Furthermore, we find that there is an appreciable background shift between reimmersions on the same unit. When small incremental conductance or resistance changes are being observed,[2,3] reimmersion can cause distortions (up to 100%) in the data. The present technique eliminates this problem. The apparatus for measuring incremental resistance, dV/dI, has been described previously.[6] Improvement in the electronic technique, such as the digital lock-in detector, has given more resolution in the incremental resistance curves. Because the output signal is also independent of the bias scan rate, spurious shifts in the resistance traces have been eliminated.[7]

The incremental resistance (dV/dI) of some typical InP, GaP, and GaAs diodes is plotted (directly from recorder traces) against voltage for different temperatures in Fig. 1. The normalizing resistance of the background, R_b, is the resistance at zero bias at the lowest temperature, T_b, at which structure is not observed. The individual characteristics of each of the four sets of curves will be considered first, and then they will be compared.

Figure 1(a) (InP) shows highly symmetric curves which are termed "broad 'Λ' (lambda) curves." No undershoot below the background, as in the Pb salt case,[4] has been found, and since there is no crossover in the curves, the area under the bell increases with decreasing temperature. The resistance peak is a very sensitive function of temperature. In fact, the largest incremental resistance changes have been observed in the InP diodes. The

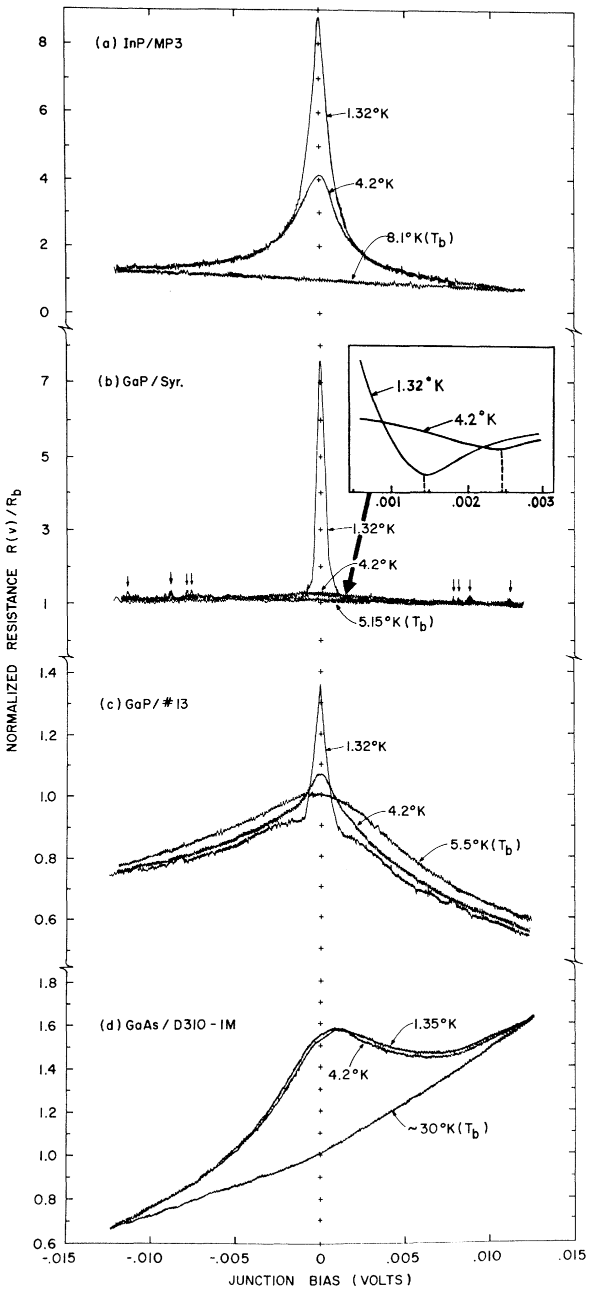

FIG. 1. The resistance $R(V)$ (normalized to the zero-bias background resistance, R_b) plotted against bias for four typical III-V compound tunnel junctions at the temperatures indicated. T_b is the washout temperature for the effect.

curves do not change in magnetic fields up to 14 kG.

The GaP curves in Fig. 1(b) are also highly symmetric but have different characteristics. The shape (as revealed by expanded plots which are shown) is actually a resistance "W" with undershoot below background. While the resistance peak is also a very sensitive function of temperature, there is curve crossover and narrowing of the bell shape with decreasing temperature. Symmetric spike structure, similar to (but weaker than) that found in the lead salts,[4] is found in GaP and is indicated by arrows. The spike structure and "W" shape are found to be magnetic-field sensitive. Magnetic-field studies with the field oriented in the plane of the junction show that, typically, the resistance "W" at 14 kG is decreased to 50% of its zero-field value.

Figure 1(c) (GaP) shows an interesting double effect. The curve is actually a resistance "W" overlapping with a very broad "Λ". The "W" portion has the same characteristics as in Fig. 1(b), while the broad-base "Λ" is considerably wider than the one associated with InP in Fig. 1(a), and is also magnetic-field insensitive. Weak spike structure has also been observed which may be associated with the "W" portion of the curve, rather than the broad base.

For the diffused GaAs case in Fig. 1(d), the bell-shaped curves are very broad "Λ's" on a fairly steep sloping background. This is true of all GaAs units investigated so far. The interesting feature is that the curve shows almost no temperature dependence below 4.2°K and has an extremely high washout temperature (T_b). No spike structure has been seen with these diodes.

On the basis of the descriptions just given, it becomes obvious that at least three separate resistance effects have been observed. The broad "Λ" in InP clearly bears no resemblance to the narrow "W" in GaP. A voltage-dependence analysis of the shapes indicates a simple empirical logarithmic dependence for $R(V)$, but the temperature dependence of the slopes is vastly different for the two cases. The very broad "Λ" effects seen in Figs. 1(c) and 1(d) are also characteristically different from either the InP "Λ" or GaP "W." The broad "Λ" effects may have a common origin, although it should be recalled that GaP has an indirect bandgap, while GaAs is direct and tunneling transitions are not likely to be similar. The fact that there is more than one effect and that they can occur simultaneously in the same diode is illustrated by the GaP curves in Fig. 1(c).

The effect of temperature on zero-bias resistance in InP and GaP has been studied in detail. The normalized resistance increment

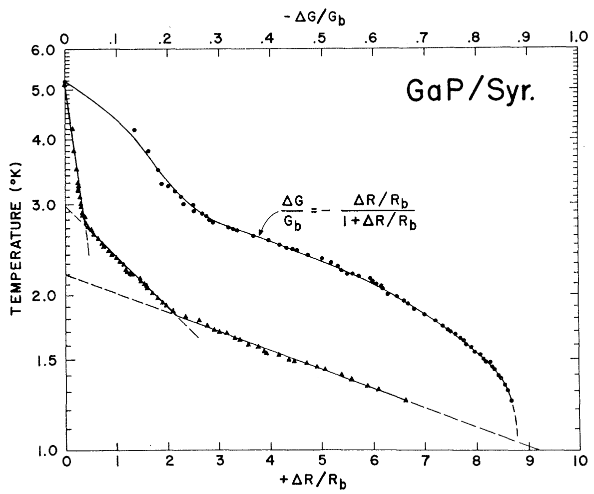

FIG. 2. A plot of the normalized resistance increment $\Delta R/R_b$ and the normalized conductance increment $\Delta G/G_b$ against log$T$ for the GaP junction Syr.

$\{\Delta R/R_b = [R(V=0)/R_b] - 1\}$ is plotted as a function of temperature in Fig. 2 for the GaP diode of Fig. 1(b). As has been discussed previously,[4] it is not obvious how data should be presented since no theory exists for the effects under consideration. Therefore, we are forced to compare our data, in the simplest case, with temperature-independent-background models, even though we observe finite background shifts and background shifts may be implicit in the final explanations of the effects. While the phenomenological model of Wyatt[3] predicts a logarithmic temperature dependence for the incremental conductance, it has been shown[4] that previous evidence offered for it is either ambiguous[3] or invalid[2] because either the background shift is too large, the effect is too small, the temperature range is too limited, or the number of data points is too small. In the data being presented, the background shift is small (1%), the effect very large (incremental changes of up to 1180%), and the number of data points large (typically about 70), so that comparison with some temperature-independent-background model is valid. The question of which model is not easily answered. The resistance data of Fig. 2 have been converted to conductance and plotted in this fashion as well. As seen, the resistance curve can be fitted by three straight lines while the conductance curve cannot be fitted in any simple way. The experimental data were also plotted in four additional ways to determine whether any other simple fits could be found. The conclusion reached from the six plots was that the three-segment log$T$ behavior in Fig. 2 was the only simple empirical description for the experimental results. The breaks are real and are not caused by instrumentation. Very similar curves (three straight-line segments) have been seen on InP diodes.

The results obtained will now be summarized:

(1) At least three different types of resistance curves have been found experimentally: (a) The "W" curves in GaP are similar to those found in the lead salts. Temperature, voltage, and (especially) magnetic-field dependence of the "W" curves suggest superconductivity, although the data do not fit the simple BCS theory. One possibility which may give agreement is superconductivity with a lifetime effect.[8] (b) The largest resistance changes yet reported (1180%) occured in InP which displayed a broad "Λ" curve. These broad "Λ" curves are most probably caused by the effect of impurities on the density of states at and near the unperturbed band edge.[9] (c) Work on diffused GaAs diodes shows a very broad "Λ" which is not temperature sensitive. The broad "Λ" observed in GaP may be of this type also.

(2) Spike structure, similar to (though much weaker than) that in the Pb salts, has been found in GaP but not in InP. This type of voltage structure has also been seen in InSb[10] and in superconducting metal-oxide-metal sandwiches.[11] These spikes (seen out as far as ±35 meV) are magnetic-field sensitive and can be split in fields of a few kG. They are found only with the "W" curves. Our observations of the voltage polarity symmetry and splitting in a magnetic field indicate that these spikes are a fundamental effect.

(3) Empirically, it has been found that for InP and GaP the incremental zero-bias resistance exhibits a three-segment logarithmic temperature dependence, even though the effects have markedly different origins. This indicates that reliance should not be placed on temperature measurements alone. In fact, temperature, voltage, and magnetic-field dependences must be used together to uniquely distinguish between the different effects that can occur.

(4) Previous interpretations[2] have been restricted to one effect: density of states with constant tunnel probability. No agreement has been found with Wyatt's model for the three effects reported in this Letter.

In conclusion, we have tried to show that there exist very large resistance anomalies which are not due to superconductivity and for which there are no theoretical explanations available. These effects are found in lightly degenerate semiconductors and their magnitudes are sensitive to impurity concentration. Contrary to previous assumptions that there is only one type of anomaly, we find that there are several, and careful experiments are necessary to separate them.

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[5]We would like to acknowledge our gratitude to R. N. Hall and J. Racette for generously providing the alloy diodes, and to D. Dumin for the diffused diodes.

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CHARGE SPECTRUM OF RECOILING ^{216}Po IN THE α DECAY OF ^{220}Rn*

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(Received 31 March 1965)

The influence of α decay on the electronic structure of the recoil atom is ideally studied in ^{220}Rn because of its gaseous state. The monoenergetic 116.5-keV nuclear recoil enables one to use electrostatic charge separation without momentum analysis in a magnetic field.

Figure 1 gives the schema of the charge spectrometer. Prior to operation, the apparatus

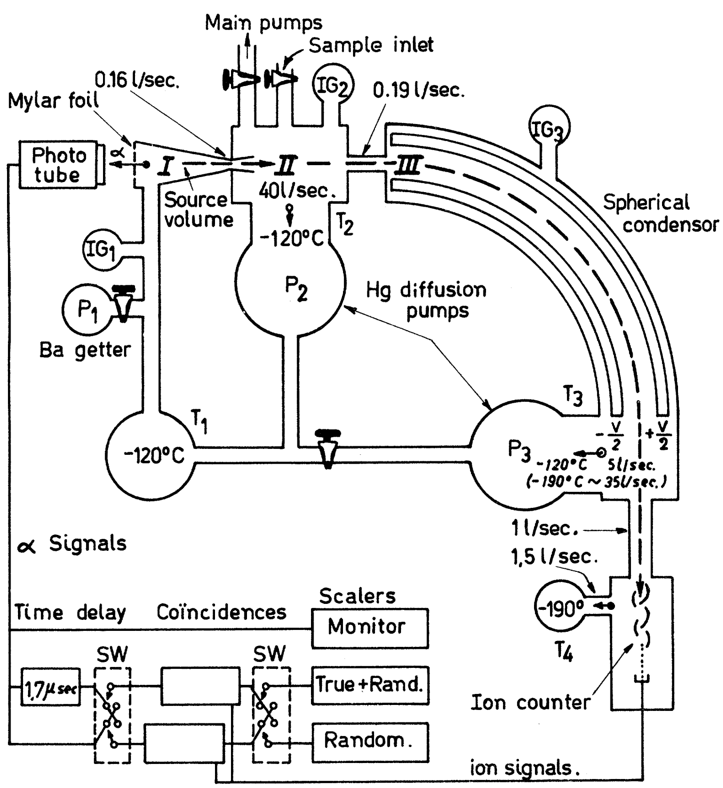

FIG. 1. Schema of the recoil spectrometer (not to scale). If cold trap T_3 is filled with liquid air, the pumping speed of "stage 3" rises to 35 litres/sec for Rn by condensation of this gas.