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Transient Behavior of the Ohmic Contact

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Under certain conditions the response time of a solid for current transients may be determined by the properties of the injecting contact rather than of the bulk. In this case it is the time required for readjustment of the space-charge barrier at the contact for delivery of the new steady-state current. The critical parameter determining the response time of the contact is the total amount of excess charge within one Debye length of the potential minimum in the space-charge barrier. Trapped, as well as free, excess charge must be included in the calculation of the Debye length. The product of gain (G) and band width ($1/\tau_0$) for a photoconductor whose response time is contact-controlled is derived and expressed in the "universal" form $G/\tau_0=M/\tau_r$, where τ_r is the dielectric relaxation time under operating conditions.

I. INTRODUCTION

THE ohmic contact is operationally defined as one that is experimentally "invisible," that is, as one that plays no role in electrical measurements on materials. Actually this operational criterion refers to steady, dc or low-frequency, measurements. Notwithstanding our intuitive expectations, there is no *a priori* reason why the ohmic contact should be equally invisible in *transient* electrical measurements. Indeed Van Heerden[1] has already shown experimentally that the transient current flow in highly resistive, copper-doped germanium is markedly sensitive to the nature of the ohmic contact. In this paper we analyze the behavior of the ohmic, injecting[2] contact for transient currents produced at fixed voltage. Such transients occur when the free-carrier density in the solid is changed by some exciting agent such as absorbed light or impacting particles, that is, in photoconductivity or bombardment-induced conductivity.[3]

The response time of the contact for current transients is the time required for readjustment of the space-charge barrier at the contact for delivery of the new steady-state current. We show, in the following section, that the critical parameter determining this response time, for current transients at fixed voltage, is the total amount of excess charge within one Debye length of the potential minimum in the space-charge barrier. Trapped, as well as free, excess charge must be included in the calculation of the Debye length. Because of this close relationship between the response time of the contact and the space-charge distribution in the contact, it should be possible to utilize response-time measurements to probe the electronic structure of the contact. Here, of course, it is necessary that the ohmic contact, rather than the bulk, control the over-all response of the series combination, contact plus bulk.

The analysis of the response time of the contact in Sec. II presupposes the existence of a potential minimum (energy maximum) inside the crystal. In the appendix the analysis is modified to cover the situation, brought about by a sufficiently high applied voltage, where there is no minimum inside the crystal. In this region it is shown that the response time of the contact is proportional to the applied voltage up to voltages drawing saturation current from the contact.

In Sec. III the results of this paper are related to those of the companion paper[4] in which bulk-controlled response times are studied. A gain-bandwidth relation for contact-controlled photoconductivity is derived and expressed in the "universal" form of Eq. (5) of I:

$$\text{gain}\times\text{band width}=\frac{M}{\text{dielectric relaxation time}}. \quad (1)$$

The factor M depends on the properties of the agent controlling the response time, in the present case the agent being the contact. The dielectric relaxation time is evaluated under the conditions of operation. An important conclusion is that contact control of the response time is possible only if the value of M in Eq. (1), corresponding to *volume control* of the response time, exceeds unity. It is only recently that measurements yielding $M>1$ have been made (see references 16 and 17 of I).

II. RESPONSE TIME OF THE OHMIC, INJECTING CONTACT

The ohmic, injecting contact is illustrated in a schematic energy-band diagram in Fig. 1. This contact is injecting for electrons, which, for the sake of definiteness, we assume, throughout this report, are the majority carriers. In (a) the contact is shown in thermal and electrical (no applied voltage) equilibrium. $\bar{E}_F$, $\bar{E}_t$, and $\bar{E}_c$ denote the Fermi level, a discrete trap level, and the bottom of the conduction band, respectively.

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[1] P. J. Van Heerden, Phys. Rev. **108**, 230 (1957).

[2] A blocking (exhaustion-layer) contact can also function as an injecting, ohmic contact, via the tunneling mechanism, if it is thin enough. This type of contact is not studied in this report.

[3] Impact ionization transients usually are produced by a change of voltage across the solid. If a steady, bias voltage is used so that the field in the solid is just below the breakdown field, then the additional voltage needed to produce the breakdown is quite small. The resulting current transient is then of the type analyzed in this report as regards the role of the ohmic contact.

[4] A. Rose and M. A. Lampert, preceding paper [Phys. Rev. **113**, 1227 (1959)]. This paper is hereafter referred to in the text as I.

In the region of the contact, defined by the downward-bending portion of the energy bands, there is excess negative charge, both free and trapped. With a voltage applied across the solid, the bands are tilted, as illustrated, in (b) and there appears the well-known potential minimum, or maximum in the energy-band diagram. The analysis, which follows, of the dynamical relationship of the space charge in the contact, particularly in the vicinity of the energy maximum, to current flow elucidates the mechanism of transient response of the contact.

A closer look is taken, in Fig. 2, of the injecting contact under current-flow conditions. The upper curve is the profile of the bottom of the conduction band with an Ohm's law current J_0 flowing at some steady-state value of volume excitation. At the maximum-energy point P_0, the electric field intensity vanishes and the current J_0 must be a pure diffusion current.

We first study the case of the rise-time transient. Let the excitation be increased so as to double, in the steady state, the density of free electrons in the volume, the applied voltage being held fixed. Correspondingly, the current J will double in the steady state. The time it takes to reach[5] the new steady-state value is defined as the rise time $\tau_{0,c}$ of the contact. Here we assume, of course, that the bulk-determined rise time is shorter that that of the contact. In order to deliver the increased diffusion current, the energy maximum must shift to the left and downwards to a new position P. Since in this region the current is approximately a pure diffusion current, the amount of downward shifting V is readily estimated from the well-known formula describing forward injection currents:

$$J/J_0=\exp(V/V_{\text{th}})=2, \quad \text{with} \quad V_{\text{th}}=kT/e.$$

This gives $V/V_{\text{th}}=\ln 2$.

The important fact to observe for our problem is that lines of force of excess negative charge lying to the right of the energy maximum are directed to the right, terminating on positive charges on the anode. Likewise the lines of force of excess negative charge lying to the left of the energy maximum are directed to the left and terminate on the cathode. [In the thermal-equilibrium situation, corresponding to Fig. 1(a), *all* lines of force from the excess negative charge in the contact are directed to the left and terminate on the cathode.] It is clear that, in the course of doubling the current, the lines of force of all the excess negative charge in the cross-hatched region, Fig. 2, between the initial and final locations of the energy maximum, P_0 and P, respectively, must transfer their allegiance from positive charges lying to the left of P_0 to positive charges lying to the right of P. Since this transfer takes place at fixed anode voltage, the positive charges required to effect the transfer must be generated by the increased excitation. The time it takes for the exciting mechanism to create the required positive charges is the rise time of the contact.

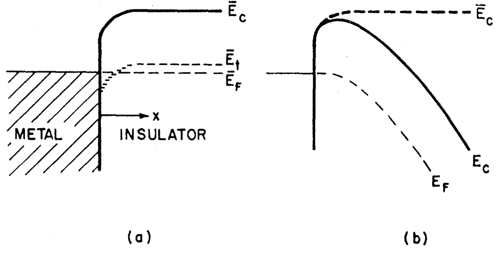

FIG. 1. Ohmic (injecting) contact, (a) in thermal equilibrium, and (b) with an applied voltage.

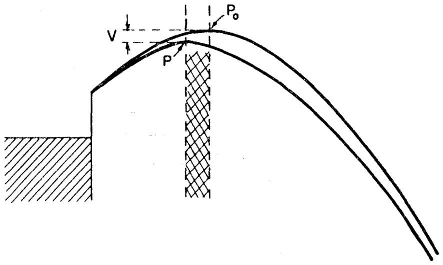

FIG. 2. Ohmic contact, with an applied voltage, showing the change in the potential minimum (energy maximum) required for an increase in current through the solid.

The amount of excess negative charge in the cross-hatched region of Fig. 2 is easily calculated. The Poisson equation $\epsilon d^2V/dx^2=eN_T$, relates the change in energy of the maximum, eV, to the shift in its location, x, the total excess charge density (free plus trapped), eN_T, at the energy maximum, and the dielectric constant ϵ. This gives directly, $V=eN_Tx^2/2\epsilon$, where N_T has been taken as constant since we are interested in small x. Thus the previous requirement $V/V_{\text{th}}=\ln 2$ can be written $x^2/2\Lambda^2=\ln 2$ or $x\simeq\Lambda$ with $\Lambda=(\epsilon kT/e^2N_T)^{\frac{1}{2}}$. Λ will be recognized as a "Debye length," corresponding however to N_T rather than just the free charge. The total number of negative charges whose lines of force must be transferred is $\mathfrak{N}_{T,c}=AN_T\Lambda=A(\epsilon kTN_T/e^2)^{\frac{1}{2}}$, where A is the cross-sectional area of the specimen. The manner in which the exciting mechanism creates the extra positive charges needed to lower the energy maximum is the following. Through the increase in excitation there is an increment F in the total rate of generation of electrons. The extra holes are either already localized in states out of which the electrons were excited, or, if initially free, are rapidly captured in traps or recombination centers. Since the contact is delivering a diffusion current J_0 sufficient to replenish only the *original* steady-state number of free electrons, the extra number made by the increment in excitation are swept out of the solid to the anode. The captured holes left behind constitute the positive

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[5] Strictly speaking some fixed fraction, such as $(1-e^{-1})$, of the final steady-state value of the current should be taken to define the rise time. In the context of the approximate analyses of this paper, this contributes a negligible correction.

charge needed to lower the contact barrier and permit a higher diffusion current. We have here assumed, obviously, that the total number of recombination centers exceeds $\mathfrak{N}_{T,c}$. We would expect this to be true in most cases of interest. The time it takes for $\mathfrak{N}_{T,c}$ negative charges in the contact to transfer their lines of force is obviously

$$\tau_{0,c}=\frac{\mathfrak{N}_{T,c}}{F}=\frac{AN_T\Lambda}{F}=\frac{A}{F}\left(\frac{\epsilon kTN_T}{e^2}\right)^{\frac{1}{2}}. \qquad (2)$$

Strictly speaking, the lowering of the barrier and the concomitant readjustment of the bulk positive charge producing the lowering should be described by a differential equation. In the steady state the bulk is neutral, the final readjustments of excess charge being confined to the neighborhood of the contact. Hence, after a long time $t\gg\tau_{0,c}$ the solution to the differential equation must yield no positive charge in the bulk. Since we have defined response time with reference to current changes of only a factor of two, there is no significant error made in ignoring the differential equation and proceeding in the approximate manner described above. In this respect, see also reference 5 and the appendix of I.

The response time of the contact for transient decay is the same as for the transient rise, $\tau_{0,c}$. This is established by an argument analogous to that employed for the rise time. Here the excitation is decreased by an amount such as to produce a new steady-state current equal to one-half the original current. The contact must readjust so that the energy maximum moves to the right and upwards, namely from P to P_0 in Fig. 2. The total number of negative charges in the contact region whose lines of force must be transferred is the same as for the rise-time case, namely $\mathfrak{N}_{T,c}=AN_T\Lambda=A(\epsilon kTN_T/e^2)^{\frac{1}{2}}$. In order for this transfer to take place, an equal number of negative charges must be created, throughout the bulk, to the right of the energy maximum. Until the contact has readjusted, the original steady-state current J is maintained unchanged and so likewise is the free electron density and the trapped-electron density in quasi-thermal equilibrium with the free electrons. Therefore the rate of capture of electrons into the recombination centers is unchanged. However the rate of generation of electrons is reduced because of the reduced intensity of excitation. The unbalanced rates of electron generation and capture build up the negative charge required to shift the potential minimum. The net rate at which the excess electron density is built up in the recombination centers is $(T'/\tau_l)J'$. Here J' is the rate at which *excess* electrons are injected past the contact (i.e., the difference between initial and final currents), and T'/τ_l is the probability that an excess, injected electron is captured by a recombination center before it completes a transit across the photoconductor. (τ_l is the electron lifetime and T' its transit time.) Letting F denote the decrement in the total rate of generation of electrons due to the reduction in excitation, and noting that the current gain $G=\tau_l/T'$, we have $J'=GF=(\tau_l/T')F$. The decay time for the contact, $\tau_{0,c}{}^d$ is then given by:

$$\tau_{0,c}{}^d=\frac{\mathfrak{N}_{T,c}}{(T'/\tau_l)J'}=\frac{\mathfrak{N}_{T,c}}{F}=\tau_{0,c}, \qquad (3)$$

where the final equality follows from Eq. (2). Because of the equality of decay and rise times, the one symbol "$\tau_{0,c}$" suffices to describe the response time of the contact.

The contact-controlled response-time transient offers a possible means to explore the space-charge distribution in the injecting contact. This possibility arises because the response time depends only on the space charge in the neighborhood (within a Debye length) of the energy maximum. But the position of the maximum within the contact is determined by the steady-state current which the contact must deliver. At a fixed level of excitation the current through the solid can, of course, be varied by changing the anode voltage. Thus, with all other conditions held fixed, the position of the maximum can be varied within the contact by changing the anode voltage. Therefore a measurement of response time *versus* voltage is indirectly a measurement of the *local* space charge in the injecting contact, provided the response time is contact-controlled. Since most of the space charge is usually in traps, the measurement of space charge becomes a measurement of trap density near the contact interface. Conversely, if the measured response time is found to be voltage-dependent in a range of voltages yielding Ohm's law currents in the steady state, one might well take this as an indication, if not a proof, of a contact-controlled response time.

III. PHOTOCONDUCTIVE GAIN-BANDWIDTH PRODUCT WITH CONTACT-CONTROLLED RESPONSE TIME

If the response time for photoconductivity is controlled by the injecting contact, as described above, then it is a simple matter to derive the gain-bandwidth product for the photoconductor. We need simply note that $\tau_{0,c}$ as given in Eq. (2) and the bulk-determined response time τ_0 as given in reference 14 of I have identical forms. Therefore, to obtain the gain-bandwidth product for the contact-controlled case, we need only replace $\mathfrak{N}_T$ by $\mathfrak{N}_{T,c}$ in Eq. (5) of I:

$$G(1/\tau_{0,c})=M_c/\tau_r, \quad \text{with} \quad M_c=\mathfrak{N}_A/\mathfrak{N}_{T,c}. \qquad (4)$$

Just as in I, τ_r is the dielectric relaxation time under operating conditions and $\mathfrak{N}_A$ is the total positive charge on the anode due to the applied voltage. Equation (4) is valid, of course, only so long as $\tau_{0,c}>\tau_0$(bulk), i.e., $\mathfrak{N}_{T,c}>\mathfrak{N}$(bulk). Otherwise, the gain-bandwidth product is determined by the bulk response time and is given by Eq. (5) if I. An important and immediate conclusion from the foregoing analysis is that contact control of the photoconductive rise time is possible only if the bulk-determined M value, M_b, exceeds unity. For contact control requires $M_c < M_b$. On the other hand, $1 < M_c$ since $\mathfrak{N}_A$ equals the *total* negative charge to the right of the energy maximum, whereas $\mathfrak{N}_{T,c}$ equals the negative charge within a single Debye length of the energy maximum.

APPENDIX

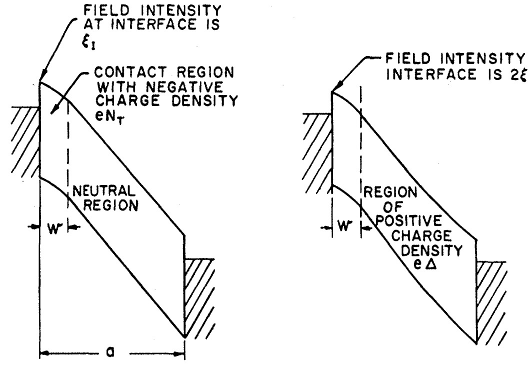
The calculation of the response time of the contact in Sec. II assumed the existence of a potential minimum inside the solid. With increasing voltage the minimum moves closer to the cathode interface and finally, at some critical voltage V_{cr} dependent on the intensity of excitation, the minimum appears right at the interface. At some higher voltage, V_s, a saturation current, independent of excitation intensity, is drawn and is equal to the random thermal current from the electrode into the solid. (Here we are assuming that breakdown has not intervened.) At voltages V intermediate between V_{cr} and V_s, the current varies with voltage V and there is no potential minimum inside the solid. This is the voltage region over which we want to extend the response-time calculation.

We consider the case, illustrated in Fig. 3(a), where the excess charge is still localized near the cathode, over a region of width, w, the remainder of the sample, of width $a-w$, being neutral, with $w \ll a$. (This is the case of greatest interest. For example, as discussed in I, the space-charge-limited current region is a difficult one in which to study or exploit photoconductivity.) There is a field $\mathcal{E}_I$ at the cathode interface. The voltage across the sample is

$$V_a = \mathcal{E}_I w + \frac{1}{2}\frac{e}{\epsilon}N_T w^2 + \left(\mathcal{E}_I + \frac{e}{\epsilon}N_T w\right)(a-w). \quad \text{(A1)}$$

For the sake of simplicity we have taken the total excess-carrier density N_T (free plus trapped) in the cathode region to be a constant.

The excitation is now increased, at fixed voltage, so as to double the current in the steady state. This doubling of the current required doubling of the field intensity at the interface. (For currents below saturation, the density of free carriers at the interface cannot change significantly—it remains equal approximately to its thermal equilibrium value.) Initially in the rise-time transient this change in field intensity at the interface is brought about by positive charges created by the additional excitation throughout the volume of the solid. As previously (Sec. II), the positive charge is created via sweepout of the additional free (negative) carriers created by the additional excitation, the *original* steady-state current being unable to maintain an increase in free-carrier concentration. Let Δ be that positive-charge density, created by the additional excitation, which increases the field at the interface to magnitude $2\mathcal{E}_I$. The (unchanged) voltage V_a is now given by:



(a) STEADY-STATE (b) TRANSIENT

FIG. 3. Behavior at a contact in the Ohm's-law range when the potential minimum has moved outside the solid.

$$V_a = 2\mathcal{E}_I w + \frac{1}{2}\frac{e}{\epsilon}N_T w^2 + \left(2\mathcal{E}_I + \frac{e}{\epsilon}N_T w\right)(a-w) - \frac{e}{2\epsilon}\Delta(a^2-w^2) + \frac{e}{\epsilon}\Delta w(a-w). \quad \text{(A2)}$$

We have neglected here a change in N_T due to the additional excitation, not only because we expect this change to be small compared to N_T but also because we assume, in any case, that $w \ll a$.

Subtracting (A1) from (A2), and neglecting terms of order w/a, we obtain

$$\mathcal{E}_I \simeq \frac{e}{2\epsilon}a\Delta, \quad \text{or} \quad \Delta \simeq \frac{2\epsilon}{ea}\mathcal{E}_I. \quad \text{(A3)}$$

Since $\tau_{0,c}$ is proportional to Δ, and $\mathcal{E}_I$ is proportional to V_a (Ohm's law currents), it is concluded that the ***response time of the contact is proportional to the applied voltage in the voltage range (below saturation) over which there is no potential minimum inside the solid.***

By essentially the same line of reasoning as previously employed in the text, it can be shown that the decay time is equal to the rise time for the present case (no potential minimum in the solid). Hence we have, as previously, employed a nomenclature without reference to a rise or decay process.