Minority Carrier Extraction in Germanium*†

RALPH BRAY
Physics Department, Purdue University, Lafayette, Indiana
(Received June 20, 1955)

The concentration of minority carriers in a sample can be effectively decreased below its equilibrium value by an extraction process in which, (a) the minority carriers in the sample are swept out by an electric field in a time ≪lifetime, while (b) the minority carrier flow into the sample at the entry contact, is suppressed. Procedures are discussed for making contacts satsifying condition (b). Such contacts have low resistance, and give photovoltages of opposite polarity to that of injecting contacts. With increasing field during extraction, there is a saturation increase of sample resistance, corresponding to approximately complete minority carrier depletion. Saturation extraction suppresses the intrinsic decrease in resistivity for a range of some 50°C for a group of p-type samples with resistivities of 7 to 40 ohm-cm at 300°K. Limitations on the range of effectiveness of extraction are imposed by failure of conditions (a) and (b) to hold at higher temperatures and/or deeper in the intrinsic range. Transport and transient effects associated with extraction can be used, as with injection, for measurement of minority carrier mobility and lifetime. Extraction is further useful for controlling collector contact properties, and for determining the composition of reverse current of point contact rectifiers, in terms of hole and electron components.

I. INTRODUCTION

THE concentration of free minority carriers in germanium may be made to deviate from equilibrium value by various means. Since, in the absence of trapping, there is an equivalent deviation in free majority carrier concentration due to requirements of neutrality, one can speak of deviations in hole-electron pair concentration. As is well known, the concentration of hole-electron pairs can be increased above the equilibrium value by optical excitation within the fundamental absorption band, or by injection of minority carriers at a p-n junction or a metal contact. It is also possible by several procedures to decrease the concentration of hole-electron pairs below the equilibrium value. We shall use the term "extraction" to represent whatever process produces such carrier depletion. We refer only to depletion occurring over a region without appreciable space charge. Complete depletion corresponds to extraction of all hole-electron pairs, leaving behind only the majority carriers of extrinsic origin. The change in conductivity due to extraction increases very rapidly as the sample approaches intrinsic behavior. Extraction may be an effective and useful auxiliary to injection for modulating bulk and contact properties.

Three types of extraction may be distinguished:

(1) Extraction, which utilizes the Suhl[1] effect, has been described in great detail by Welker.[2] Electrons and holes in germanium are deflected in crossed electric and magnetic fields to a surface of high recombination velocity. If they recombine there more rapidly than they can be generated in the bulk or at the other surfaces, the concentration of hole-electron pairs in the sample is reduced.

(2) Extraction from the vicinity of *reverse-biased rectifying contacts* has been reported by Banbury[3] for the case of point contacts on lead sulphide and germanium and by Angello and Ebert[4] for p-n junctions in germanium. According to rectifier theory,[5,6] the reverse current may consist in whole or in part of a diffusion of thermally generated minority carriers to the junction. This would lead to depletion of minority carriers over a distance of the order of a diffusion length from the junction, when reverse voltage is applied. A general statement of the condition for depletion at reverse-biased junctions has been given by van Roosbroeck.[7]

(3) In the method of extraction[8,9] to be discussed in this paper,‡ special contacts on n- or p-type germanium are prepared which severely limit the current of minority carriers entering the sample, while imposing no barrier to majority carriers. Consequently, when an electric field is established in the sample, the minority

* Work supported by a Signal Corps contract.

† Preliminary accounts of this work were presented at the American Institute of Electrical Engineers and the Institute of Radio Engineers, Semiconductor Devices Research Conference, Minneapolis, Minnesota, June, 1954, and the Chicago meeting of the American Physical Society, November, 1954. [Phys. Rev. **98**, 229 (1955).]

[1] H. Suhl and W. Shockley, Phys. Rev. **76**, 180 (1949).

[2] H. Welker, Z. Naturforsch. **6(a)**, 184 (1951); also, E. Weisshaar and H. Welker, Z. Naturforsch. **8(a)** 681 (1953).

[3] P. C. Banbury, Proc. Phys. Soc. (London) **B66**, 50 (1953). The term "extraction" was first used by Banbury to apply to this process.

[4] S. J. Angello and T. E. Ebert, Phys. Rev. **96**, 221 (1954). They called the effect "egression."

[5] W. J. Bardeen and W. H. Brattain, Phys. Rev. **75**, 1208 (1949).

[6] W. Shockley, *Electrons and Holes in Semiconductors* (D. Van Nostrand Company, Inc., New York, 1950), Chap. 4.

[7] W. van Roosbroeck, Phys. Rev. **91**, 282 (1953).

[8] All future references to "extraction" in this paper will be to type (3), except where specifically noted. Subsequent to the initiation of this work, it was brought to my attention by I. M. Ross that extraction by this mechanism had been observed in the course of experiments with unipolar transistors by G. Dacey and I. M. Ross, Proc. Inst. Radio Engrs. **41**, 970 (1953).

[9] Gibson has reported extraction in near-intrinsic n-type germanium, to which specially doped contacts were grown. A. G. Gibson, Physica **20**, 1058 (1954); also, Arthur, Bardsley, Brown, and Gibson, Proc. Phys. Soc. (London) **B68**, 43 (1955).

‡ *Note added in proof.*—Recently, it has been suggested that extraction of this type be called *carrier exclusion* [G. G. E. Low, Proc. Phys. Soc. (London) **B68**, 310 (1955)].

carriers which are normally present in the interior can be swept out of the sample at the exit contact without being replenished at the entry contact. If the sweepout rate is greater than the rate at which minority carriers are thermally regenerated in the sample, then appreciable depletion of minority carrier concentration can be achieved throughout the sample. This is in contrast to extraction of type (2) above, where depletion originates and is localized at the minority carrier exit contact. Almost complete depletion was obtained with electric fields well under 50 volts/cm on samples one to two cm in length, and with minority carrier lifetime of the order of 100 μsec. Increase of resistance by as much as a factor of about 13, corresponding to extraction of about 90% of *all* the carriers, was observed at 65°C for a sample having a resistivity of 32 ohm-cm at room temperature.

II. THEORY

The nature of the contact to the semiconductor determines whether there occurs the well-known injection, or the extraction, of minority carriers when forward[10] voltage is applied.

Extraction will occur if the net minority carrier current entering the sample, I_{nc}, is *less* than the instantaneous minority carrier current established in the interior when the voltage is applied. The latter is given by

$$I_{n0}=n_0 e\mu_n E, \tag{1}$$

where n_0 is the equilibrium minority carrier concentration in the sample, μ_n is the corresponding mobility, and E is the electric field in the interior. Since fewer minority carriers are entering the sample than are being swept away from the entry contact, a deficit in concentration is established at the edge of this contact, and swept into the interior. For ideal extraction, the entering minority carrier current is completely suppressed: i.e., $I_{nc}=0$. The contact may be characterized by the parameter γ_c, the ratio of minority carrier current to total current at the contact. The significant quantity for a contact is actually $\gamma_c-\gamma_0$, where γ_0 is a constant representing the same ratio in the interior, and defined for equilibrium carrier concentrations; i.e.,

$$\gamma_0=n_0 b/(p_0+n_0 b), \tag{2}$$

where n_0 and p_0 are the interior, equilibrium, minority and majority carrier concentrations,[11] respectively, and b is the ratio of minority to majority carrier mobility, μ_n/μ_p. Thus, the condition $(\gamma_c-\gamma_0)>0$ corresponds to injection, and $(\gamma_c-\gamma_0)<0$ to extraction.

The condition for extraction may be realized in general at any boundary in a sample between regions of low and high concentration of minority carriers. At such a boundary, the minority carrier current into the region of high concentration is limited, and extensive depletion can occur in the latter region. Such a boundary cannot hinder the flow of majority carriers, and consequently the boundary resistance must be small.

A specific example will now be considered for the case of a metal contact on p-type germanium. The boundary condition here is established at the surface of the sample. The conditions for injection and extraction are compared, as illustrated in Fig. 1.

The equilibrium potential energy diagrams show the conduction and valence bands bending down at the contact for the case of injection, and bending in the reverse direction for extraction. The direction of the barrier at the surface depends on the germanium surface treatment and the interaction between this surface and the metal. At the injection contact, the minority carrier concentration, n_c, is greater than n_0; if forward voltage is applied, part of its appears across the barrier in the semiconductor, thereby decreasing it and permitting propagation of excess electrons into the interior.

In contrast, at the extraction contact, there is a surface layer which is strongly p-type, producing a boundary where $n_c \ll n_0$. When forward voltage is applied, it appears predominantly across the bulk, and a deficit in concentration is swept into the interior, as illustrated.

The condition for extraction can also be satisfied at a junction, formed inside a crystal, by low- and high-resistivity material of the same type. Not only can extensive depletion occur in the latter region, but localized depletion of type (2) can simultaneously occur on the edge of the low-resistivity side.

Methods of producing contacts for extraction will be discussed in the next section.

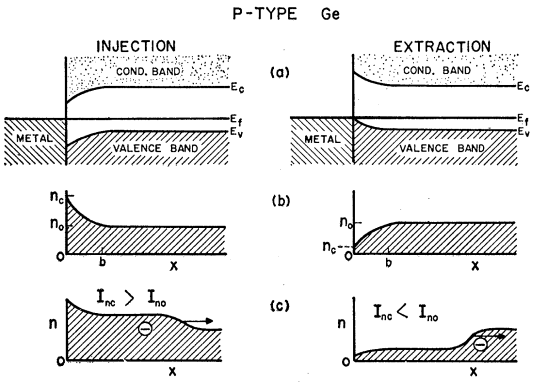

FIG. 1. The schematic diagram compares conditions for injection and extraction at a metal contact on p-type Ge. (a) Equilibrium potential energy diagrams comparing direction of the barrier at the contact. (b) The equilibrium electron concentration along the sample. (c) The propagation of an excess or a deficit concentraction of electrons from the negative contact into the interior by a large sweeping field.

[10] The term "forward voltage" is used here to represent that polarity of the applied voltage at the contact, for which minority carriers flow into the semiconductor.

[11] The notation here is that usually taken for p-type material, but since we have not specifically identified the minority carrier, the equations, as defined in the text, are valid for either n- or p-type Ge.

Extraction of minority carriers was studied experimentally mainly in terms of the transient and steady state changes produced in sample conductance as a function of voltage and temperature. An expression for the change in conductance G, in terms of parameters of the sample is derived below for the linear, one-dimensional case. The sample is taken to be in the form of a bar of length L, and rectangular cross section A. Low-resistance, area contacts are made at the ends of the sample.

The solution is obtained in the approximation that the continuity equations are linear, which is valid[12] under the condition $n_0 \ll p_0$. Then, if a pulse of constant voltage, V, is applied to the sample, the electric field, E, being uniform and constant during extraction, is given by V/L. The change of conductance, ΔG, is independent of the spatial distribution of the deficit in carrier concentration in the sample. For simplicity, diffusion is neglected.

When the pulse is applied to the sample, at $t=0$, a minority carrier current,

$$I_{nc}=n_b e\mu_n E \tag{3}$$

is introduced in the sample at the edge of the forward-biased contact, at $x=b$. Elsewhere in the sample the minority current is still I_{n0}. A change in minority carrier concentration, Δn, is quickly established at $x=b$, such that,

$$\Delta n/n_0=(n_b-n_0)/n_0=(I_{nc}-I_{n0})/I_{n0}. \tag{4}$$

If $\Delta G/G_0 \ll 1$, then

$$\Delta n/n_0=(\gamma_c-\gamma_0)/\gamma_0. \tag{4a}$$

Here, Δn represents either an increase or decrease in concentration, depending on whether $(\gamma_c-\gamma_0)>0$ or $(\gamma_c-\gamma_0)<0$.

In either case, Δn is swept into the interior with constant velocity, $v=\mu_n E$. As it proceeds, the magnitude of Δn decays exponentially in time, with the decay constant given by τ, the minority carrier lifetime in the sample. The decay is due to excess recombination or thermal generation, depending on whether $\Delta n>0$ or $\Delta n<0$.

The steady-state condition is attained when the perturbation reaches the end of the sample after a time, $t_s=L/v$, which may be called the transit time. The total change in the number of minority carriers in the sample, ΔN, is obtained by integrating the deficit over the whole sample. For $t<t_s$, we get

$$\Delta N=Av\tau\Delta n[1-\exp(-t/\tau)]. \tag{5}$$

The change of conductance is

$$\Delta G=e\Delta N(b+1)\mu_p L^{-2}. \tag{6}$$

[12] The conditions for linearity have been thoroughly discussed by van Roosbroeck (reference 7).

On combining Eqs. (4), (5), and (6), we have the expression for the transient change of conductance,

$$\frac{\Delta G}{G_0}=(\gamma_c-\gamma_0)\frac{b+1}{b}\frac{v\tau}{L}[1-\exp(-t/\tau)]. \tag{7}$$

The dependence of $\Delta G/G_0$ on E in the steady state, $t \geq t_s$, is given by

$$\frac{\Delta G}{G_0}=(\gamma_c-\gamma_0)\frac{b+1}{b}\frac{\mu_n E\tau}{L}[1-\exp(-L/\mu_n E\tau)]. \tag{8}$$

Of the several parameters of the sample, γ_0, may be calculated from the conductivity, and τ and μ_n may be measured independently. However, γ_c is an unknown, determined by the height and structure of the barrier, and it may be voltage dependent. Its general form will be deduced from the experimental dependence of $\Delta G/G_0$ on E. For ideal extraction, $\gamma_c \to 0$ and then, as $L/\mu E\tau \to 0$,

$$\frac{\Delta G}{G_0} \to \left(\frac{\Delta G}{G_0}\right)_{\max}=-\frac{b+1}{b}\gamma_0=-\frac{n_0(b+1)}{p_0+n_0 b}, \tag{9}$$

which is the maximum change due to extraction.

III. THE CONTACT

A. Methods of Formation

Early experiments on near-intrinsic p- and n-type germanium to which low-resistance contacts had been soldered, revealed unpredictable injecting or extracting behavior of the contacts. These observations led to the study of extraction, and of techniques for obtaining reproducible behavior as regards injection or extraction with low-resistance contacts.

Most of the contact experiments were made with relatively high-resistivity samples (20–40 ohm-cm) at room temperature. The greatest reproducibility in results was obtained when contacts were made to surfaces which had been strongly etched with, e.g., CP_4.

The results obtained with various types of contacts are summarized in Table I, where the contacts are

TABLE I. Behavior of different contacts on n- and p-type Ge, with respect to the production of injection (I) or extraction (E).

	Type of contact[a]	n-type Ge	p-type Ge
I	Silver paint	I	E
	Rhodium plate	I	E
	Point contacts of tungsten or phosphor bronze	I	E,I
II	Indium solder (L.T.)[b]	I	E
	Indium solder (H.T.)[c]	I	E
	Tin solder (L.T.)	I	E
	Tin solder (H.T.)	E	I

[a] Except as indicated, all contacts were large area contacts.
[b] (L.T.) represents "low temperature," for contacts soldered very close to the melting point of the particular solder.
[c] (H.T.) represents a "high-temperature" treatment of contacts initially formed at L.T. This treatment consisted of heating on a hot plate at 300°C for one or more minutes in air.

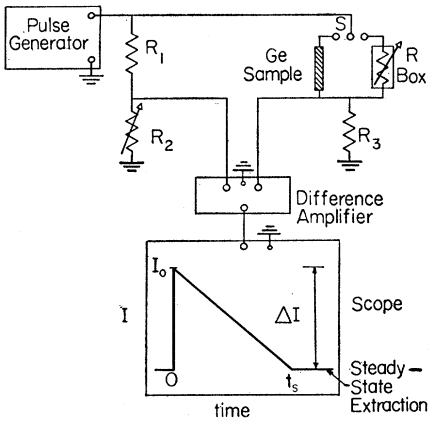

FIG. 2. Arrangement of pulse bridge circuit for observing change of current with time during extraction. The resistance of the sample is measured at any time by switching S from sample to standard-resistance box. Change of current for linear case is illustrated. The abrupt transition to steady-state current gives the transit time, t_s, for minority carriers.

divided into two classes. Those of class II are soldered, while those of class I are mechanically applied or electroplated. In the latter case the properties of the contact depend on the barrier already present at the free surface of the germanium and its possible modification by the presence of the metal contact. The silver-paint and rhodium-plated contacts invariably gave injection (and rectification) on n-type Ge, in accordance with the concept of a p-type surface inversion layer on n-type Ge. These contacts usually gave extraction on p-type samples.[13] This suggests the presence of a strong p-type layer also on the surface of p-type Ge. Pressure contacts with tungsten or phosphor-bronze whiskers gave results consistent with the above on n-type Ge, but gave erratic effects on p-type Ge. In the latter case, both injection and extraction contacts were obtainable. These were not stable and could be converted one into the other with slight physical disturbances.

The most reproducible behavior was obtained with contacts made by soldering pure tin or indium at slightly above their melting points to well-etched surfaces. With such low temperature, "L. T.," soldered contacts, extraction was invariably obtained on p-type and injection on n-type Ge. Area contacts of this type usually showed negligible contact resistance. Heat treating such contacts at about 300°C in air for about one minute converted the tin contacts so that they gave injection on p-type, and extraction on n-type. No conversion was obtained for indium contacts. Conversion upon heating was, however, also obtained with several commercial solder mixtures containing tin, including a tin and indium mixture. The early unpredictability of behavior of soldered contacts is therefore traceable mainly to the dependence on the temperature of soldering. Such heat-treated contacts are designated "H. T."

It seems likely that when conversion is observed with H.T. contacts, it is due to doping of the contact region with donors, producing n-type layers on both p- and n-type Ge.

No attempt was made to definitely identify the donor, although it seems to be associated with the presence of tin.[14] Neither has the cause of the p-type behavior of the L.T. contacts been determined. In this case, appreciable influx of acceptors is not expected in the few seconds the contacts are heated at $T<200$°C. Surface effects are likely to be predominant here.

Deliberate doping to make contact regions which are of the same type as the bulk, but more extrinsic, is a recognized technique for suppressing excess minority carrier injection. Such junctions are usually made at appreciably higher temperatures ($T>400$°C) than those reported here, and may also be expected to give extraction. Gibson *et al.*[9] obtained extraction with junctions made by growing a long, heavily-doped n-type section onto one end of a near-intrinsic n-type crystal.

B. Contact Photovoltage

The sign of the photovoltage generated at a contact should depend on the direction of bending of the energy bands at the contact. As Fig. 1 illustrates, the bending of the bands at the contact on the semiconductor side is expected to be in opposite directions for injection and extraction. It is expected, then, that the sign of the open-circuit photovoltage would have opposite polarity for these two types of contacts. Photovoltaic polarity tests were made on extracting and injecting contacts, using silver paint and soldered contacts. Under illumination, the metal contact became negative for injection and positive for extraction contacts on p-type Ge. As expected, just the reverse effects were found for contacts on n-type Ge. The photovoltages were all very small compared to those obtained on high-resistance contacts and had to be observed under strong illumination with white light.

IV. BULK CONDUCTANCE EXPERIMENTS

In this section, the measurements of the changes in bulk conductance during extraction of minority carriers are described. The dependence of transient and steady-state changes on voltage and temperature was explored for samples of various resitivities.

[13] Complications were observed with silver paint contacts. There was appreciable contact resistance, of order of 20% of the total sample resistance. Furthermore, when fields ~50 volts/cm were applied, sudden conversion from extraction to very strong injection could be observed. With successive applications of voltage, conversion occurred at lower voltages.

[14] W. C. Dunlap, Jr., has commented (personal communication) that attempts at the General Electric Research Laboratories to grow germanium crystals with tin as an impurity, have failed to show any acceptor or donor activity on the part of the tin.

A. Method

All the experiments described below were performed with p-type germanium. The samples were bars, one to two cm long, with rectangular cross sections, about 2 mm on a side; extracting end contacts were made by soldering with indium by the low-temperature procedure. The resistance of the whole sample was measured in the bridge-type circuit illustrated in Fig. 2. Pulse technique was necessary not only to observe transient effects, but also to minimize heating effects in steady-state measurements at high voltages.

The pulse generator was a low-impedance source giving pulses up to 100 volts across the sample, with pulse lengths variable between 0.1 μsec and 1000 μsec. The detector in the bridge is a Tektronix difference amplifier whose output is observed on an oscilloscope. Either the total sample current can be displayed from the voltage drop across the small resistor, R_3, or the amplified change in current during extraction can be observed by adjusting R_2.

The steady-state resistance was measured by substituting a variable standard-resistance box for the sample. This procedure makes the measurement independent of any discrepancies in the gain of the difference amplifiers, and of the calibration of the resistances in the arms of the bridge.

B. Approach to Steady-State Extraction

The approach to steady state under extraction conditions is followed by observing the change of current with time for constant voltage applied across the sample. This change reflects the decrease in conductance as the deficit in carrier concentration moves through the sample. The rate of decay of current with time is described by Eq. (7). In general, this decay is nonlinear, and terminates at $t=t_s$, when the deficit concentration reaches the end of the sample. However, if $t_s \ll \tau$, there is a linear decay with sharp termination. This is illustrated in Figs. 3(a) and 3(b) by oscillographs of the change in current *vs* time. From the measurement of t_s, the minority-carrier drift mobility is readily determined, and found to give good agreement with standard values.[15]

The above discussion and Eq. (7) are valid as long as $n_0 \ll p_0$. When n_0 becomes appreciable, as the temperature rises, or if the sample is strongly illuminated, the current decay greatly increases in amplitude, becomes strongly nonlinear, and t_s increases appreciably. All these features are illustrated in Fig. 3(c) for the same sample as used for 3(a) and 3(b), but strongly illuminated. The lower trace in Fig. 3(c) shows the dark current on the same scale.

Essentially similar effects have been observed and

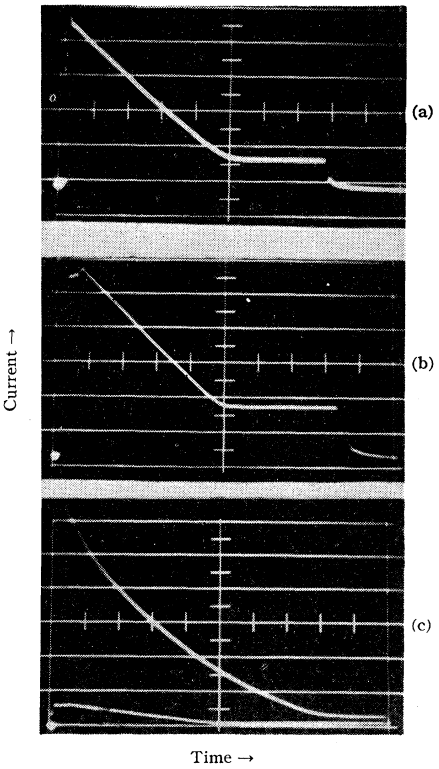

FIG. 3. Current decay characteristics during extraction in p-type Ge sample, $\rho=23$ ohm-cm, $L=1.38$ cm, $T=297°$K; curves (a) and (b) correspond to sample in the dark, curve (c) in strong illumination. (a) Somewhat nonlinear: $V=14.7$ volts, $t_s=35$ μsec, $\mu_n=3700$ cm^2/volt sec. (b) Linear: $V=51$ volts, $t_s=10$ μsec, $\mu_n=3700$ cm^2/volt sec. (c) Strongly nonlinear: $V=51$ volts, $t_s\approx 16$ μsec; compare with smaller trace representing dark characteristic on same scale.

explained[7,16] in terms of the decrease in the velocity of transport of a given concentration of minority carriers as $n_0 \rightarrow p_0$. This transport velocity may become much smaller than the carrier drift velocity. This phenomenon is very important for extraction, since it imposes a limitation on its practicability as a sample approaches deeper into the intrinsic range.

This limitation becomes evident from examination of the general expression for the transport velocity[17] of the minority-carrier concentration,

$$v(I,n)=\frac{I\mu_n}{e\mu_p(p_0-n_0)[1+(b+1)n_0/(p_0-n_0)]^2}, \quad (7)$$

where I is the total current density. Not only is the transport velocity, v, low at the beginning of a constant-voltage pulse if $n_0 \rightarrow p_0$, but v becomes still smaller as I decreases during the extraction pulse. This means the carriers are being swept out with progressively smaller sweep field due to conductivity modulation. This essentially accounts for the nonlinearity of the decay.

[15] Similar observations, but with weakly injecting contacts, have been reported by A. Many, Proc. Phys. Soc. (London) **B67**, 9 (1954), and for extracting contacts by J. B. Arthur *et al.* (reference 9).

[16] M. B. Prince, Phys. Rev. **91**, 271 (1953). This paper also contains previous relevant references.

[17] See reference 6, p. 329.

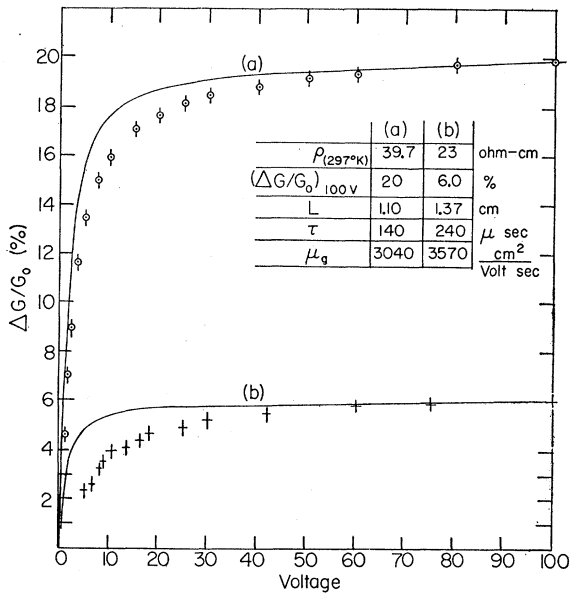

FIG. 4. The relative change of conductance upon extraction *vs* the voltage applied across *p*-type Ge samples. Experimental data is given by circles and crosses. Solid curves are calculated from Eq. (8) using the data given in the chart, and assuming γ_c is voltage independent. Deviation between calculated curve and experiment is ascribed to voltage dependence of γ_c.

When the transit time in such circumstances becomes so large that $t_s > \tau$, then the sweepout of minority carriers during extraction becomes ineffective. This has been observed for samples deep in the intrinsic range.

C. Steady-State Extraction—Voltage Dependence

The experimental dependence of the steady-state change of conductance upon sample voltage is shown in Fig. 4, for two *p*-type samples, having resistivities of 39.7 and 23 ohm-cm, respectively, at 297°K. Other relevant data for the sample are tabulated on the figure. The plotted data is to be compared with the solid curves, which represent $\Delta G/G_0$ calculated according to Eq. (5). In the calculation, τ was obtained from an independent measurement,[18] and E was set equal to V/L. Instead of the carrier drift mobility, $\mu_n \simeq 3800$ cm²/volt sec, the pulse drift mobility,[19] μ_g, was calculated and used. This serves as a partial correction for the fact that n_0 is appreciable in these samples. For the term $(\gamma_c - \gamma_0)(b+1)/b$, where γ_c is the unknown, the experimental value of $\Delta G/G_0$ at 100 volts (where $L/\mu_n E\tau \ll 1$) was used. The solid curves were drawn as if the value of γ_c so obtained, was independent of voltage. The calculated curves show a more rapid rise and saturation with voltage than is shown by the experimental data. Most of this discrepancy is attributed to a dependence on voltage for γ_c; the form of this dependence is readily obtained. Thus for the 23 ohm-cm sample, γ_c turns out to be appreciably greater than zero at low voltage (for $V \sim 5$ volts, $\gamma_c \sim \gamma_0/2$) but decreases with increasing voltage,[20] and either saturates or becomes very small as V becomes greater than 50 volts. For the other sample, the discrepancy is smaller, implying γ_c at low voltage is already small and close to its saturation value. The fact that Eq. (5) is a poorer approximation in this case, where n_0 is much larger, is partially responsible for the discrepancy. In the next section it is shown for several samples, that for temperature below 340°K, $\gamma_c \sim 0$, at least for $V \sim 100$ volts.

It is clearly desirable for efficient extraction, that $\Delta G/G_0$ rise and saturate rapidly with increasing voltage. The efficiency of extraction thus depends on how large the lifetime is, and on how rapidly γ_c decreases and approaches zero. The latter is determined by the structure of the particular contact barrier. For example, if the barrier is thin, and if I_{cs} is the thermal emission current of minority carriers across the contact into the semiconductor, then, with bulk diffusion current neglected, it is easily shown that

$$\gamma_c/\gamma_0 = I_{cs}/(I_{cs} + n_0 e \mu_n E). \tag{8}$$

Here, γ_c will decrease with increasing field. The smaller I_{cs}, the smaller is the field at which extraction becomes effective.

D. Dependence of Extraction on Resistivity and Temperature

Temperature-dependence curves of normal resistivity, ρ_0, and resistivity after extraction, ρ_e, are shown in Fig. 5 for four samples which have ρ_0 between 7.0 and 37.9 ohm-cm at 300°K. Measurements of ρ_e were made at pulse voltages of about 100 volts to provide saturation extraction where possible. While ρ_0 goes through a maximum and begins to decrease approximately exponentially with temperature as the sample enters the intrinsic range, ρ_e continues to increase along the low-temperature, extrinsic-range curve. Only at higher temperatures, between 340° and 360°K for these particular samples, does ρ_e reach a maximum, and then it decreases rapidly. Ratios of ρ_e/ρ_0 as high as 13 were achieved. This corresponds to extraction of about 8 out of every 9 carriers in the sample.

To determine how close extraction comes to removing all hole-electron pairs of intrinsic origin, the data of Fig. 5 were compared with calculations of the change in conductivity corresponding to complete depletion. The calculations were based on Eq. (9); the parameters n_0, p_0, and b were obtained from the normal sample resistivity, and the most recent empirical data of Morin and Maita[21] for the magnitude and temperature de-

[18] The method used is that described in Sec. IV E.

[19] The values of μ_g (given on Fig. 4) are obtained from $\mu_n/[1+(\Delta G/G_0)_{max}]$. The correction is small when $n_0 \ll p_0$. The larger the correction, the less valid is Eq. (5). Thus, Eq. (5) is a better approximation for the 23 ohm-cm sample than for the 39.7 ohm-cm sample.

[20] A. Many has measured γ_c for weakly *injecting* contacts, and found it to increase with voltage (reference 15).

[21] E. J. Morin and J. P. Maita, Phys. Rev. 94, 1525 (1954).

pendence of the n_0p_0 product and of mobility. The solid curves in Fig. 6 represent the calculated values of $\Delta\sigma/\sigma_0$ at various temperatures between 300° and 340°K for samples with normal resistivities between 7 and 40 ohm-cm at 300°K. It can be seen that the measured values fit well to the curves, indicating that depletion is almost complete in this temperature range. Thus, under the various conditions of this experiment, it may be concluded that $\gamma_c \rightarrow 0$ at high voltage.

Extraction suppresses the intrinsic rise in minority carrier density for a range of some 50°K. There are several factors limiting the range over which extraction is effective. The difficulty with transport of minority carriers as the sample becomes more intrinsic, as $n_0 \rightarrow p_0$, was discussed in Sec. IV B. Another important factor is the structure of the extraction contact itself. It may be expected that the emission current at the entry contact, I_{cs}, will increase with temperature, thereby increasing γ_c, and making extraction less effective. For the samples investigated here, the peak in ρ_e occurred at temperatures where the transit time was still appreciably less than the lifetime. The bending over of ρ_e as temperature increases must then be due to the contacts. However, at somewhat higher temperatures, it is observed that the transit time does become very large, thereby invoking the transport limitation, causing ρ_e to drop even more rapidly.

E. Recovery after Extraction

After the extracting voltage pulse is over, there is recovery to equilibrium concentrations by thermal generation of hole-electron pairs in the sample. If a small constant measuring current passes through the sample, the decay in sample voltage (proportional to resistance) during recovery may be observed on an oscilloscope. From this decay, the minority carrier lifetime is readily determined. The technique is the same as has already been described for measuring lifetime from recovery after injection.[22] By making injecting contact on one end of a sample, and extracting contact on the other end, it was possible to compare decay curves on the same sample after injection and after extraction. For both cases the same value of lifetime was measured, whether for etched or ground surfaces. These measurements were made only at room temperature, where $n_0 \ll p_0$.

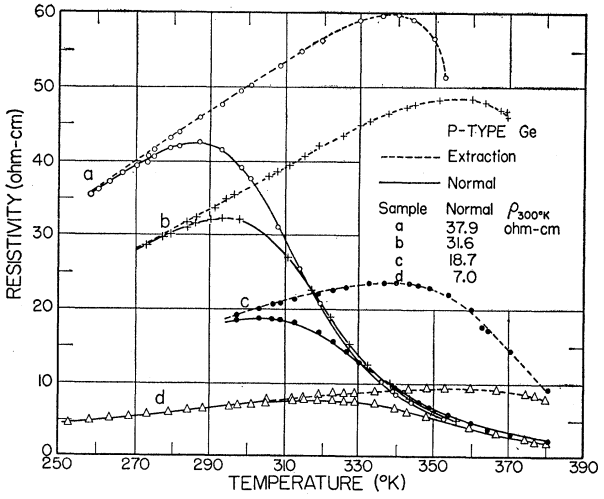

FIG. 5. Resistivity of p-type Ge samples as a function of temperature. The solid lines are for the normal resistivity measured at very small voltage or at beginning of an extraction pulse. They show the usual transition from extrinsic to intrinsic behavior. The broken lines represent the resistivity corresponding to extraction for pulse voltage of 100 volts. These show the extension of the extrinsic region and delay of intrinsic region for a temperature interval of about 50°C.

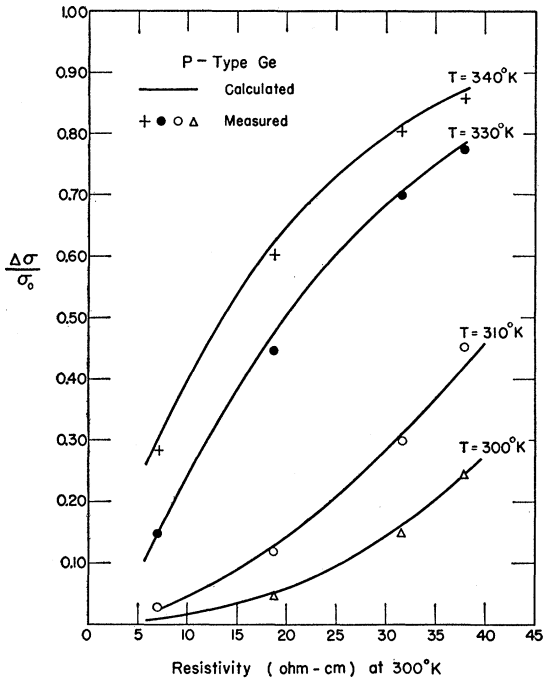

FIG. 6. The relative change in conductivity at saturation extraction, as a function of the resistivity at 300°K. Solid lines are calculated using data of Morin and Maita for p-type Ge. The measured points are taken from the curves of Fig. 5. The agreement indicates that for the particular samples and extracting contacts, there is obtained almost complete depletion of thermally generated hole-electron pairs.

V. COLLECTOR CURRENT MODULATION

As a counterpart to the effect of excess minority carrier injection, the depletion of minority carriers in the vicinity of a collector contact by some external extraction mechanism may be expected to, and does,[23] decrease the collector conductance. A collector contact may therefore be used as a probe to detect the extraction of minority carriers from a sample. In turn, ex-

[22] Navon, Bray, and Fan, Proc. Inst. Radio Engrs. 40, 1342 (1952).

[23] Such an effect, produced by different extraction procedures, has been reported by Shockley (reference 6, p. 66), and Angello and Ebert (reference 4).

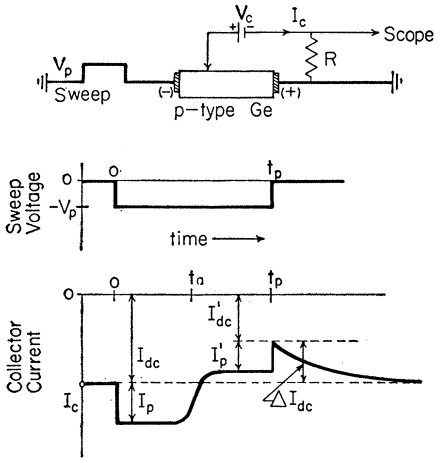

FIG. 7. Arrangement for studying the collector conductance modulation during extraction of minority carriers from the sample. The change of collector current with time for constant sweep voltage is illustrated. There is a decrease of collector current upon minority carrier depletion, and a subsequent recovery when thermal generation restores equilibrium minority-carrier concentration.

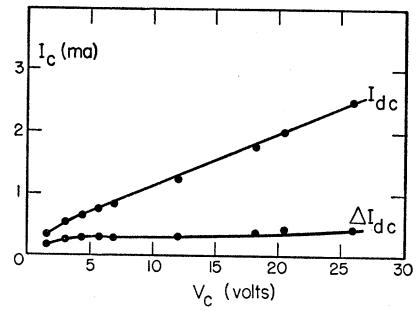

FIG. 8. Collector current as a function of reverse bias on a collector point contact (phosphor-bronze on p-type germanium). I_{dc} is the normal collector current. ΔI_{dc} is the change of collector current at the given bias, due to minority carrier depletion. Minority carriers in bulk are responsible for only part of total reverse collector current.

traction is useful for determining the composition of reverse current in a collector. To the extent that the collector conductance is sensitive to minority carrier depletion, extraction can be used to modulate the collector conductance.

The arrangement used for investigating the influence of extraction of minority carriers from a sample on a collector contact is shown in Fig. 7. Extraction contacts are soldered to the ends of a Ge sample. A pulsed electric field controls the degree of minority carrier extraction from the sample. The collector is a metal point-contact rectifier; the collector current, I_c, is observed on the oscilloscope.

For a constant voltage pulse of duration t_p, the time dependence of collector current is shown in Fig. 7. For $t<0$, there is a collector current, I_{dc}, corresponding to a given dc collector bias, V_c. At $t\geq 0$, there is an additional collector current I_p, due to added biasing effect by the pulse voltage. At time, t_a, the deficit in minority carrier concentration arrives at the collector; I_c decreases to I_c'. It stays constant again until time, t_p, when the pulse voltage drops to zero; I_p' drops to zero, leaving I_{dc}'. This is the collector current at the given dc bias, for the condition of depleted minority-carrier concentration in the sample. I_{dc}' then recovers to its steady-state value, I_{dc}.

The composition of the reverse current for the collector is deduced from the I_c curve. The change in reverse current at a given dc bias, due to extraction of minority carriers from the sample, is represented by ΔI_{dc}. It may therefore be associated with that part of the reverse current due to diffusion of thermally generated minority carriers from the bulk to the contact. It was observed that even for complete depletion, ΔI_{dc} was appreciably less than I_{dc}. For collectors made with tungsten and phosphor-bronze whiskers on 20–40 ohm-cm, p- and n-type samples having lifetimes of several hundred microseconds, $\Delta I_{dc}/I_{dc}$ was rarely more than 0.5, and usually less, at room temperature, and in the dark.

This ratio can depend on the collector reverse bias, as is illustrated in Fig. 8 by curves of I_{dc} and ΔI_{dc}, *vs* V_c, for a phosphor-bronze contact to p-type Ge. The characteristics were taken at room temperature in the dark. In this case, I_{dc} increases almost linearly with reverse bias, while ΔI_{dc} is nearly constant. It is to be expected, however, that behavior of this kind may vary considerably with surface treatment and the forming of the rectifier contact.

It may be concluded that, under the conditions described above, most of the collector reverse current is composed of majority carrier and/or surface leakage current. However, when the minority carrier concentration in the sample is made much larger, most of the reverse current can be composed of minority carriers, and then extraction is much more effective in controlling the collector properties. This is readily shown by illuminating the collector so that the reverse resistance is greatly decreased. Upon extraction, it is possible to restore and even exceed the dark resistance.

VI. SUMMARY AND APPLICATIONS

Two conditions have been established for the effective extraction of minority carriers from germanium: (a) the injection efficiency, γ_c, at the entry contact must be close to zero, and (b) the minority carriers in the sample must be swept out in a time $\ll\tau$. With a series of p-type samples (7–40 ohm-cm at 300°K), to which *In* contacts were soldered, these conditions were generally satisfied for $T\lesssim 370$°K; complete minority carrier depletion was obtained for $T\lesssim 340$°K. The decrease in effectiveness of extraction at higher temperature and/or deeper in the intrinsic range is attributed to increase in γ_c with temperature, and the decrease in the transport velocity of the minority carrier concentration as $n_0\rightarrow p_0$. Within its range of effectiveness, extraction is a useful supple-

ment to injection for modulating bulk and contact properties. Transient and transport effects associated with extraction can be used for measuring minority carrier drift mobility and lifetime. A special feature of extraction is its usefulness in extending the temperature range of operation of diodes and transistors. This may be accomplished with an auxiliary, extraction electrode and sweep field, or more simply, if less efficiently, by utilizing a base contact which satisfies the condition for extraction. In the latter case, when reverse current at the collector is high enough to permit appreciable field in the base region, considerable minority carrier depletion, and consequent enhancement of reverse resistance of the collector can be observed. Thus an extraction base contact, not only suppresses undesirable excess minority-carrier injection, but it also depresses the minority-carrier current which would normally be present.

ACKNOWLEDGMENTS

The author wishes to express his appreciation to Professor K. Lark-Horovitz and Professor H. Y. Fan for their interest and discussions.

PHYSICAL REVIEW VOLUME 100, NUMBER 4 NOVEMBER 15, 1955

Effect of Shape Anisotropy on the Coercive Force of Elongated Single-Magnetic-Domain Iron Particles

T. O. PAINE, L. I. MENDELSOHN, AND F. E. LUBORSKY
Measurements Laboratory, General Electric Company, Lynn, Massachusetts

(Received April 19, 1955)

Elongated single-magnetic-domain iron particles, 150 angstrom units in diameter, have been prepared with properties that definitely confirm the existence of a shape anisotropy effect on coercive force. This conclusion is based upon four observations: (1) Torque curve analysis shows the predominating anisotropy effect to be uniaxial. (2) With increasing particle elongation, the temperature coefficient of coercive force departs from the temperature coefficient of crystal anisotropy and approaches the temperature coefficient of saturation induction. (3) Coercive forces greater than 2000 oersteds for iron have been measured. (4) A direct correlation is observed between particle coercive force and elongation.

I. INTRODUCTION

A BETTER understanding of the basic factors which determine the properties of high-coercive-force magnetic materials is emerging from studies of submicroscopic ferromagnetic particles, too small to contain magnetic domain boundaries. These "single-domain particles" cannot change their magnetization in response to an externally applied field by the relatively easy process of domain boundary movement, in the manner of soft magnetic materials, but respond to a field by the more difficult process of rotating their magnetization vectors. The magnetic anisotropy effects, opposing domain rotation, thus determine the coercive force of these particles.[1] Although the sources of magnetic anisotropy are not completely understood, four effects have been suggested: magnetocrystalline anisotropy,[2] strain anisotropy,[3,4] shape anisotropy,[4] and surface anisotropy.[5] The existence of these proposed anisotropy effects has not been experimentally confirmed, with the exception of crystal anisotropy, which was conclusively demonstrated in an investigation of the coercive force of fine particles of manganese-bismuth by Guillaud.[2] Crystal anisotropy has also been studied in iron by Néel[6] and in barium-iron oxide and related compounds by Went *et al.*[7]

It is now eight years since Stoner and Wohlfarth,[4] Néel,[8] and Guillaud[3] first suggested that the shape anisotropy of an elongated single-domain particle of iron should be more than ten times as great as its crystal anisotropy. Although the existence of shape anisotropy has not been confirmed experimentally during this time, Weil,[9,10] Galt,[11] and Meiklejohn[12] have attributed discrepancies between observed and calculated coercive force values to a possible shape-anisotropy effect arising from statistical fluctuations in particle dimensions, and Nesbitt[13,14] and Kronenberg[15] have established the presence of an elongated precipitate

[1] C. Kittel, Phys. Rev. **70**, 965 (1946); see also Revs. Modern Phys. **21**, 541 (1949).
[2] C. Guillaud, thesis, Strasbourg, 1943 (unpublished).
[3] C. Guillaud, J. phys. radium **8**, 347 (1947).
[4] E. Stoner and E. Wohlfarth, Trans. Roy. Soc. (London) **A240**, 599 (1948).
[5] L. Néel, Compt. rend. **237**, 23 (1953).
[6] L. Néel, Compt. rend. **224**, 1488 (1947).
[7] Went, Rathenau, Gorter, and van Oosterhout, Phillips Tech. Rev. **13**, 194 (1952).
[8] L. Néel, Compt. rend. **224**, 1550 (1947).
[9] L. Weil and S. Marfoure, J. phys. et radium **8**, 358 (1947).
[10] L. Weil, International Powder Metallurgy Day, Graz, July, 1948, No. 17 (unpublished).
[11] J. Galt, Phys. Rev. **77**, 845 (1950).
[12] W. Meiklejohn, Revs. Modern Phys. **25**, 302 (1953).
[13] Nesbitt, Williams, and Bozorth, J. Appl. Phys. **25**, 1014 (1954).
[14] E. Nesbitt and P. Heindenreich, Elec. Eng. **71**, No. 6, 530 (1952).
[15] K. J. Kronenberg, Z. Metallkunde **45**, 440 (1954).

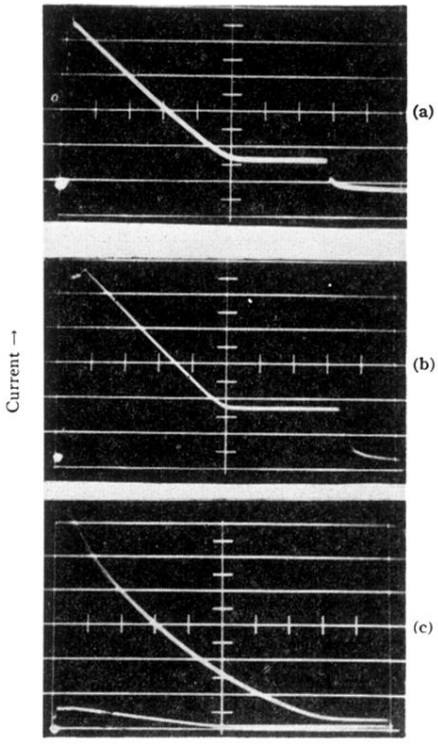

FIG. 3. Current decay characteristics during extraction in p-type Ge sample, $\rho=23$ ohm-cm, $L=1.38$ cm, $T=297°K$; curves (a) and (b) correspond to sample in the dark, curve (c) in strong illumination. (a) Somewhat nonlinear: $V=14.7$ volts, $t_s=35$ μsec, $\mu_n=3700$ cm^2/volt sec. (b) Linear: $V=51$ volts, $t_s=10$ μsec, $\mu_n=3700$ cm^2/volt sec. (c) Strongly nonlinear: $V=51$ volts, $t_s\approx16$ μsec; compare with smaller trace representing dark characteristic on same scale.