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HEAVY DOPING EFFECTS IN HIGH EFFICIENCY SILICON SOLAR CELLS

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EXTENDED ABSTRACT

We study the temperature dependence of the emitter saturation current for bipolar devices by varying the surface recombination velocity at the emitter surface. From this dependence we derive a value for the bandgap narrowing that is in better agreement with other determinations than were previous results obtained from the temperature dependence measured on devices with ohmic contacts.

We report results of a first direct measurement of the minority-carrier transit time in a transparent heavily doped emitter layer. The value was obtained by a high-frequency conductance method recently developed and used for low-doped Si. The transit time coupled with the steady-state current enables the determination of the quasi-static charge stored in the emitter and the quasi-static emitter capacitance. Using a transport model, we estimated, from the measured transit time, the value for the minority-carrier diffusion coefficient and mobility. The measurements were done using a heavily doped emitter of the Si p^+-n-p bipolar transistor. The new result indicates that the position-averaged minority-carrier diffusion coefficients may be much smaller than the corresponding majority-carrier values for emitters having a concentration ranging from about 3×10^{19} cm^{-3} to 10^{20} cm^{-3}.

We present experimental evidence for significantly greater charge storage in highly excited silicon near room temperature than conventional theory would predict. The experiments used low-doped collector regions of silicon bipolar transistors subjected to strong electrical excitations yielding an electron-hole plasma having electron-hole-pair densities up to about 4×10^{18} cm^{-3}. As a possible interpretation, we connect these findings to a significant bandgap narrowing ΔE_G ($\approx$ 80 meV at 4×10^{18} cm^{-3}). These data are compared with various data for ΔE_G in heavily doped silicon. Important implications result for silicon solar cells under concentrated illumination.

1. COMMENTS ON DETERMINATION OF BANDGAP NARROWING FROM ACTIVATION PLOTS

I. INTRODUCTION

Various experimental methods exist to determine bandgap contraction and minority carrier mobility and diffusivity in heavily doped silicon, parameters that play a central role in characterizing p-n junction diodes, transistors and solar cells. Some methods use the recombination current in the quasi-neutral emitter of a diode or transistor. These fall into two categories: (a) those that assume equality between the majority carrier and minority carrier mobilities [1]-[4]; and (b) those that avoid this assumption, which has been questioned [5],[6], by emphasizing the temperature dependence of this recombination current [7]. The latter category has produced values of bandgap reduction considerably larger than the values derived from other methods [1]-[4].

In the present study, we use method (b), attempting to improve its accuracy by varying the minority carrier surface recombination velocity at the emitter contacts of otherwise nearly identical emitters. This approach yields ΔE_G = 133 ± 6 meV (m_n^* = 1.45 m_o) and ΔE_G = 149 ± 6 meV (m_n^* = 1.1 m_o) for a Si:As emitter having an approximately space independent doping concentration of 1.0 x 10^{20} cm^{-3}. Also it yields minority carrier diffusion length, L_p = 0.23 μm. The value for ΔE_G obtained by this method shows better agreement with other determinations than do those obtained previously by us using the temperature dependence of emitter recombination currents [7].

II. A SIMPLE THEORY FOR THE INTERPRETATION OF THE EXPERIMENTAL RESULTS

We consider a uniformly doped quasi-neutral emitter region (QNE: $0 < x < W_E$) of a npn bipolar transistor. The emitter saturation current J_{SE} can be expressed as

$$J_{SE} = qn_{io}^2 \frac{D_p}{N_{Deff}} \frac{1}{L_p} \left[\frac{(S_p/D_p)L_p + \tanh(W_E/L_p)}{1+(S_p/D_p)L_p \tanh(W_E/L_p)}\right] \quad , \tag{1}$$

where S_p is the surface recombination velocity at $x = W_E$, N_{Deff} is the effective doping concentration and other symbols have their usual meanings. For large S_p ($S_p > D_p/W_E$), (1) can be approximated as

$$J_{SE}(S_p \to \infty) = qn_{io}^2 \frac{D_p}{N_{Deff}} \frac{1}{L_p} \coth(W_E/L_p) \quad . \tag{2}$$

For small S_p ($S_p < W_E/\tau_p$), (1) has the following assymptotic form:

$$J_{SE}(S_p \to 0) = qn_{io}^2 \frac{D_p}{N_{Deff}} \frac{1}{L_p} \tanh(W_E/L_p) \quad . \tag{3}$$

Usually efforts to separate N_{Deff} and D_p have involved measuring $J_{SE}(S_p \to \infty)$ for devices with shallow emitters and ohmic contacts at $x = W_E$. In the analysis of these measurements, assumptions about the values for the minority-carrier diffusion coefficient D_p were used, although the validity of these values cannot be confirmed by direct measurement.

We can avoid these uncertainties by measuring J_{SE} for a device with $S_p \to 0$ and $W_E < L_p$. In this limit, (1) reduces to

$$J_{SE}(S_p \to 0) \simeq qn_{io}^2 \frac{1}{N_{Deff}} \frac{W_E}{\tau_p} \quad . \tag{4}$$

By $S_p \to 0$, we mean that $S_p < W_E/\tau_p$. In (4), the neglect of the surface recombination velocity at $x = W_E$ means that J_{SE} is the recombination current within the volume or bulk of the quasi-neutral emitter. Dziewior and Schmid [8] measured τ_p from the photoluminiscence decay emitted from the n-type bulk silicon after excitation by a laser pulse, and showed that τ_p is independent of temperature in the range 300 K < T < 400 K. Therefore, the temperature dependence of $J_{SE}(S_p \to 0)$ is determined only by n_{io}^2/N_{Deff} where

$$n_{io}^2 = N_c N_v \exp(-E_{GI}/kT) \tag{5}$$

is the square of the standard intrinsic density, N_c and N_v are the electron and hole effective density of states and E_{GI} is the intrinsic energy gap. The temperature dependence of E_{GI} is [9]

$$E_{GI} = E_{GI}(0) - \alpha T = 1.206 - 2.8 \times 10^{-4} T(\text{eV}) \quad , \quad 300\text{ K} < T < 400\text{ K} \quad . \tag{6}$$

In (6) $E_{GI}(0)$ is the linearly extrapolated energy gap, which differs from the actual energy gap of 1.170 eV at 0 K. Assuming the rigid-band approximation and including the Fermi-Dirac statistics, we can express N_{Deff} as

$$N_{Deff} = N_D \exp(-\Delta E_G/kT)\exp(\eta_c)/F_{1/2}(\eta_c) \tag{7}$$

where ΔE_G is the reduced bandgap energy, $F_{1/2}$ is the Fermi-Dirac integral of order half and $\eta_c = (E_F - E_c)/kT$. Substituting (5), (6) and (7) into (4), we get the following relation:

$$d\ \ln\{J_{SE}(S_p \to 0)T^{-\alpha}\exp[\eta_c(T)]/F_{1/2}[\eta_c(T)\}/d(kT)^{-1}$$

$$= -[E_{GI}(0) - \Delta E_G] + (kT)^{-1} d\Delta E_G/d(kT)^{-1} \quad (\alpha = 3.0) \quad . \tag{8}$$

Comparison of ΔE_G measured by photoluminescence at 10 K [10] and around room temperature [11] shows that the values of ΔE_G are temperature independent within an experimental accuracy of about ± 10 meV. A similar temperature independence of ΔE_G was observed in optical absorption experiments [12]. Thus the second term in (8) can be neglected. Other details for extracting ΔE_G are explained in [7].

III. EXPERIMENTAL RESULTS AND DISCUSSIONS

For our experimental study, the emitter saturation currents of two npn bipolar transistors were measured in the temperature range of 300 K < T < 360 K. The two transistors have nearly uniform emitter doping profile, $N_{DD} \approx N_D = 1 \times 10^{20}$ cm^{-3} and W_E = 0.18 μm, but one (device A) has an ohmic contact at the emitter surface and the other (device B) has a polysilicon emitter contact.

Although the mechanisms underlying the improved current gain and low surface recombination velocity in transistors with polysilicon contacts are still debated in the literature, there is sufficient evidence that the surface recombination velocity at the polysilicon - monosilicon interface can be much smaller than 10^4 cm/sec [13]-[15]. A recent experimental study by Neugroschel et al. [13], using test structures with polysilicon emitter contacts similar to the polysilicon contact of device B, estimated $S_p \approx 1000$ cm/sec. As mentioned earlier, the assumption $S_p \to 0$ requires that $S_p < W_E/\tau_p$ cm/sec, which is satisfied for the device B, as discussed above.

As a first step in our procedure, the minority hole diffusion length L_p is determined from the ratio of J_{SE} for devices A and B, $J_{SE}(S_p \to \infty)/J_{SE}(S_p \to 0)$ at the same temperature. From (2) and (3),

$$L_p \approx W_E / \text{arccoth}\, [J_{SE}(S_p \to \infty)/J_{SE}(S_p \to 0)]^{1/2} \quad . \tag{9}$$

The measured ratio of $J_{SE}(S_p \to \infty)/J_{SE}(S_p \to 0)$ at 300 K was 2.4, and L_p deduced from (9) is about 0.23 µm.

The band gap shrinkage ΔE_G is obtained from the temperature dependence of device B using (4) which yields $\Delta E_G = 149 \pm 6$ meV for an electron effective mass $m_n^* = 1.1\ m_o$; $\Delta E_G = 133 \pm 6$ meV for $m_n^* = 1.45\ m_o$. The results for two values of m_n^* are given because of uncertainties about the actual value of m_n^* [7],[16].

The above value for ΔE_G was derived from the activation plot of (4), an expression that is valid for $S_p \ll W_E/\tau_p$ and $W_E/L_p \ll 1$. The measured value for L_p is about 0.23 µm, ie, $W_E/L_p \approx 0.78$. Thus, we have to investigate the temperature dependence of $(D_p/L_p)\tanh(W_E/L_p)$ in (3). This requires an assumption about the temperature dependence of D_p. We assume, for the purpose of a sensitivity study only, that D_p is proportional to T. Under this assumption the error in $\Delta E_G = 149$ meV is about 4 meV for $S_p \ll W_E/\tau_p$. The sensitivity to S_p can be established by assuming $S_p = 10^4$ cm/sec (for $W_E/L_p \ll 1$) which causes an error of about 4 meV. The combined effects of finite S_p and $W_E/L_p \lesssim 1$ for the device B were examined using (1) and found to cause an error of about +8 meV. The temperature dependence of m_n^* is very small in the temperature range used [16] and was neglected.

For the comparison of our values for ΔE_G with other experimental results, we calculated the "apparent bandgap narrowing" ΔE_G^{app} [17]. Assuming Maxwell-Boltzmann statistics, ΔE_G^{app} is defined as

$$N_{Deff} = N_D \exp(-\Delta E_G^{app}/kT) \quad . \tag{10}$$

Therefore the relation between ΔE_G^{app} and ΔE_G is

$$\Delta E_G^{app} = \Delta E_G - kT \ln[F_{1/2}(N_c) \exp(-N_c)] \quad . \tag{11}$$

This gives ΔE_G^{app} = 118 ± 6 meV when $m_n^* = 1.1\ m_o$ or 113 ± 6 meV when $m_n^* = 1.45\ m_o$ at 300 K which are in close agreement with the published values of ΔE_G^{app} shown in [17, Fig. 1].

IV. CONCLUSIONS

Transport phenomena in the heavily doped silicon were studied by measuring the emitter saturation currents for the npn transistors with two different types of emitter contacts: ohmic contacts and polysilicon contacts.

From the measurements we conclude that at $N_D = 1 \times 10^{20}\ cm^{-3}$, $L_p \approx 0.23\ \mu m$ and ΔE_G = 149 meV for $m_n^* = 1.1\ m_o$ or ΔE_G = 133 meV for $m_n^* = 1.45\ m_o$. These results correct the previous determinations [7] that yielded higher values for ΔE_G. The devices exhibited $I_B \propto \exp(qV_{BE}/kT)$ dependence over several decades of current. Thus no corrections for space-charge-region current components were required, which was not the case before [7].

A similar approach employing the temperature dependence of the emitter saturation current to obtain bandgap narrowing appeared recently in the conference literature [18] with a different discussion of the underlying assumptions than that given in the present study. In part, this conference paper differs from the work of the present study because the authors used α = 3.5 instead of α = 3.0 in (8); we base our choice of α on the condition that the bulk recombination exceeds the surface recombination in the single-crystal silicon ($S_p < W_E/\tau_p$).

The method used here can be used to explore bandgap narrowing for various doping concentrations.

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2. TRANSIT TIME AND CHARGE STORAGE MEASUREMENTS IN HEAVILY DOPED EMITTERS

I. INTRODUCTION

In this work we analyze the heavily doped emitter of a Si bipolar transistor using both the steady state and frequency responses. The standard transport measurements involve, in most cases, the measurement of only the steady-state recombination current in the heavily doped part of the p-n junction device. As an example, we consider a p^+-n junction where the heavily doped p^+-emitter is bounded by a surface with recombination velocity S_n for the electrons. We also assume that the electron transit time τ_t is much smaller than the electron lifetime τ_n, i.e. the emitter is transparent. A detailed analytical treatment of the transparent emitter with arbitrary profile $N_{AA}(x)$ was done by Shibib et al. [1] who derived the expressions for the current density J_n and τ_t. For the purpose of further discussion, we show below the expression for J_n:

$$J_n = \frac{q n_{io}^2 \exp\left[(qV/kT)-1\right]}{\int_0^{W_E} \frac{N_{Aeff}(x)}{D_n(x)}\, dx + \frac{N_{Aeff}(W_E)}{S_n}} . \qquad (1)$$

Equation (1) is identical to (8) of [1] except that the position-dependent electron diffusion coefficient $D_n(x)$ is left inside of the integral. In (1), n_{io} is the intrinsic carrier density, W_E is the thickness of the quasineutral emitter and N_{Aeff} is the effective doping density [2] $N_{Aeff} = P_o(x)(n_{io}/n_{ie})^2 = n_{io}^2/N_o(x) < P_o(x)$, where $P_o(x) \simeq N_{AA}(x)$ is the hole equilibrium concentration, N(x) is the equilibrium electron concentration, and n_{ie} is the effective intrinsic density. N_{Aeff} arises from the various heavy doping effects, such as bandgap narrowing ΔE_G, band-edge distortions, and carrier degeneracy.

Del Alamo and Swanson [3] pointed out that the ratio (N_{Aeff}/D_n) can be directly measured and thus the modeling of heavily doped regions is possible without knowing N_{Aeff} and D_n separately for a steady state current and for the devices with $S_n \to \infty$, as (1) indicates. A complete quasi-static modeling of thin emitters in bipolar devices requires, however, a separation of the emitter recombination current into a quasi-static stored charge Q_n and relevant time constants [1]

$$J_n = \frac{Q_n}{\bar{\tau}_n} + \frac{Q_n}{\tau_t} \tag{2}$$

where $\bar{\tau}_n = \int_0^{W_E} N(x)dx / \int_0^{W_E} dxN(x)/\tau_n(x)$ is the average electron lifetime and τ_t is the emitter transit time. In order to calculate $\bar{\tau}_n$, τ_t and Q_n, a precise value of $N_{Aeff}(x)$ is required even for $S_n \to \infty$ [1]. Thus, a complete quasi-static modeling of thin emitters in bipolar devices does require decoupling of D_n from N_{Aeff}.

Recently, an experimental technique for a direct measurement of τ_t in transparent emitters with $\tau_t \ll \bar{\tau}_n$ has been proposed and demonstrated [4,5]. This enables the calculation of the quasi-static charge $Q_n = J_n \tau_t$ and the quasi-static emitter capacitance $C_n = (q/kT)Q_n$, which is important for the modeling of the time and frequency responses of a bipolar transistor. From the measured value of τ_t, an average value of D_n can be obtained and the decoupling of D_n from N_{Aeff} becomes possible. This also allows, using (1), the determination of S_n for devices with non-ohmic contact, such as in transistors with polysilicon emitter contact.

The decoupling is also very important from the fundamental point of view in order to identify and study the physical mechanisms underlying the minority-carrier transport in heavily doped semiconductors, and to study their dependencies on doping, temperature, fabrication conditions, etc. Earlier attempts to decouple D from N_{eff} involved a number of assumptions [6-8], the validity of which is difficult to ascertain.

The method [4,5] for measurement of τ_t, applicable for heavily doped material, is based on the measurement of the frequency dependence of the small-signal electron conductance G_n that gives a characteristic corner (intersect) frequency ω_I:

$$\omega_I = 1/\tau_t \quad . \tag{3}$$

The corner frequency results when the reciprocal of the signal frequency becomes comparable to the hole transit time τ_t.

II. EXPERIMENTAL RESULTS

Measurement of τ_t was done on a microwave transistor with a diffused Si:B emitter with junction depth $x_j \approx 0.31$ µm, sheet resistance of about 100 Ω/square, and surface concentration $N_S \approx 1 \times 10^{20}$ cm^{-3}. The boron was diffused using a solid boron nitride source which yields profiles close to the erfc profile [9]. The transistor had ohmic metal contact with large S_n and the device area was $A = 4.7 \times 70$ µm^2. Figure 1 shows the measured and the theoretical dependencies of the emitter conductance versus frequency $f = \omega/2\pi$ plotted in normalized scale. The conductance is the real part of the common emitter small-signal input admittance y_{ie} obtained by a measurement of the S-parameters which were then converted to y-parameters by standard transformations [10]. The data were taken at 25° C using a Hewlett-Packard 8505A network analyzer. The real part of $y_{ie} = g_{ie} + jb_{ie}$ results almost completely from the recombination in the emitter and follows the treatment given in [4,5]. The measurements were performed at different values of the collector current I_C around $V_{BE} \approx 0.75$ V, where both I_C and the base current I_B followed the ideal $\exp(qV_{BE}/kT)$ dependence. The experimental results agree very well with the theoretical curve shown as a solid line. The extrapolation of the $G \propto f^{1/2}$ portion of the curve yields an intercept frequency $f_I \approx 70$ MHz and the transit time is from (3): $\tau_t \approx 2.3 \times 10^{-9}$ s. The measured saturation current density at 25°C was $J_{no} \approx 8.8 \times 10^{-13}$ A/cm^2. Hence, $Q_{no} = J_{no}\tau_t \approx 2 \times 10^{-21}$ C/cm^2 and $C_{no} \approx 8 \times 10^{-20}$ F/cm^2. These results assumed transparent emitter with $\tau_t << \bar{\tau}_n$. This assumption will be justified below.

Measurements at high frequencies can be influenced by parasitic effects, in particular by the parasitic base resistance R_B. Taking into account R_B, the input conductance from the hybrid π model is $g_{ie} \approx g_\pi + \omega^2 C_\pi^2 R_B$, where g_π and C_π are the intrinsic parameters. The measured value of the base resistance was $R_B \approx 60\ \Omega$. Using the measured values for g_{ie} and C_π, we find that the error due to R_B is only about 4% at 300 MHz and completely negligible at lower frequencies used in Fig. 1. To further demonstrate that other parasitic effects of the package are not important below 300 MHz, we show in Fig. 2 the locus of the input admittance in the complex plane as a function of frequency. The locus is a known semicircle, provided that the parasitic effects are negligible [11].

DISCUSSION

The main results of this work are the measured values for τ_t, Q_n, and C_n reported above. To decouple D_n from N_{Aeff} requires additional approximations. In the concentrations ranging from about 10^{18} cm^{-3} to 10^{20} cm^{-3}, N_{Aeff} is only a weak function of $N_{AA}(x)$ [12,13]. This results because the built-in field due to the doping density gradient is opposed by a quasifield due to the bandgap narrowing and the effective field acting on minority electrons is small. Hence, assuming $dN_{Aeff}/dx \simeq 0$ we obtain [1]

$$\tau_t \simeq W_E^2/2\bar{D}_n \tag{4}$$

where $\bar{D}_n$ is the position-averaged minority-carrier diffusion coefficient $\bar{D}_n = W_E/\int_0^{W_E} [1/D_n(x)]dx$ which emphasizes small values of $D_n(x)$, occuring near the heavily doped surface. Using the measured $\tau_t \simeq 2.3\ 10^{-9}$ s and $W_E \simeq 0.3$ µm, we obtain from (4): $\bar{D}_n \sim 0.2$ cm^2/s and $\bar{\mu}_n = (q/kT)\bar{D}_n \sim 8$ cm^2/Vs. The majority-carrier mobility corresponding to the peak surface concentration of 10^{20} cm^{-3} is about $\mu_n \simeq 60$ cm^2/Vs [14]. Numerical calculations for a Gaussian profile show that the transit time depends on the model used for $\Delta E_G(x)$ [1]. Therefore, the "field-free" model $dN_{Aeff}/dx \simeq 0$ [12] yielding (4) gives only a rough estimate of $\bar{D}_n$. Nevertheless, the values obtained suggest that the minority-carrier diffusivities and mobilities may be much smaller than the corresponding majority-carrier values in a concentration range from about 10^{19} cm^{-3} to 10^{20} cm^{-3}. Scattering and trapping of the minority carriers by the localized bandtail states of the minority band was suggested as a possible mechanism causing the low minority carrier mobility [8,15]. A qualitative support for the trap-controlled mobility model was obtained recently by measuring the activation behaviour of µ(minority) [16]. One theoretical model, which does not consider the effects of the bandtail, predicts higher minority carrier mobility than the corresponding majority carrier values [17]. Our value is in good agreement with the results of Burk and de La Torre [18] obtained indirectly from measured diffusion length and Auger lifetime of Dziewior and Schmid [19], but is smaller than the results of del Alamo et al. [20] who measured both diffusion length and lifetime. Since $\bar{D}$ is now determined, (1) yields $\bar{N}_{Aeff} \simeq 2 \times 10^{17}$ cm^{-3} for the p^+ emitter; $N_{Aeff}/\bar{D}_n$ agrees with data in [21]. Further analysis of the factors determining N_{Aeff}, which include the bandgap narrowing, can be based on the value obtained, with additional assumptions.

To check the condition $\tau_t \ll \bar{\tau}_n$, required for transparency, we use the N_{Aeff}/D_n data of Slotboom and DeGraaf [21] for p^+ silicon and assume that the electron lifetime in the heavily doped p^+ emitter is dominated by the Auger process for which $\tau_n(x) = \tau_A(x) = 1/C_p P_o^2(x)$, where $C_p = 9.9 \times 10^{-32}$ cm^{6}s^{-1} [19]. From a numerical simulation we find that $\tau_t/\bar{\tau}_n \simeq 0.15$ for $\bar{D}_n \simeq 0.2$ cm^2/s. The majority carrier value of $\bar{D}_n \simeq 2$ cm^2/s gives $\tau_t/\bar{\tau}_n \simeq 0.015$. The transparency of the emitter studied is thus assured. The error in obtaining $\bar{D}_n$ from f_I in Fig. 1 for $\tau_t/\bar{\tau}_n \simeq 0.15$ is only about 1.5% [5]. The high-frequency conductance method used here applies for frequencies $f \gtrsim 10/2\pi\bar{\tau}_n \gtrsim 100$ MHz [4], which is self-consistent with the $G \propto f^{1/2}$ range in Fig. 1.

SUMMARY

The transit time τ_t of minority carriers across the thin and heavily doped p^+ emitter of bipolar transistor was directly measured using a high-frequency dependence of a small-signal input admittance. The transit time, coupled with (N_{eff}/D), which is determined from measured steady state current, allows a complete quasi-static characterization of the minority carrier transport in thin heavily doped emitters under both steady state and transient excitations. The weighted average value for the minority carrier diffusion coefficient and mobility in the heavily doped material was also estimated.

The frequency response of the conductance can also be applied for a narrow p^+ or n^+ region contacted by a layer with low recombination velocity S instead of an ohmic contact. An example is a polysilicon emitter contact. The analysis that can be used for this case to reveal the bulk and surface parameters of heavily doped emitters will be published elsewhere together with a treatment that avoids the field-free approximation.

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SECTION 2 FIGURE CAPTIONS

Fig. 1 Input conductance of bipolar transistor versus frequency. The solid line shows the theoretical curve following $G \propto f^{1/2}$ at high frequencies. The extrapolation of the theoretical line yields $f_I \simeq$ 70 MHz and $\tau_t \simeq 2.3 \times 10^{-9}$ s for the 0.3 μm thick emitter.

Fig. 2 The locus of the common-emitter input admittance in a complex plane as a function of frequency for the transistor from Fig. 1.

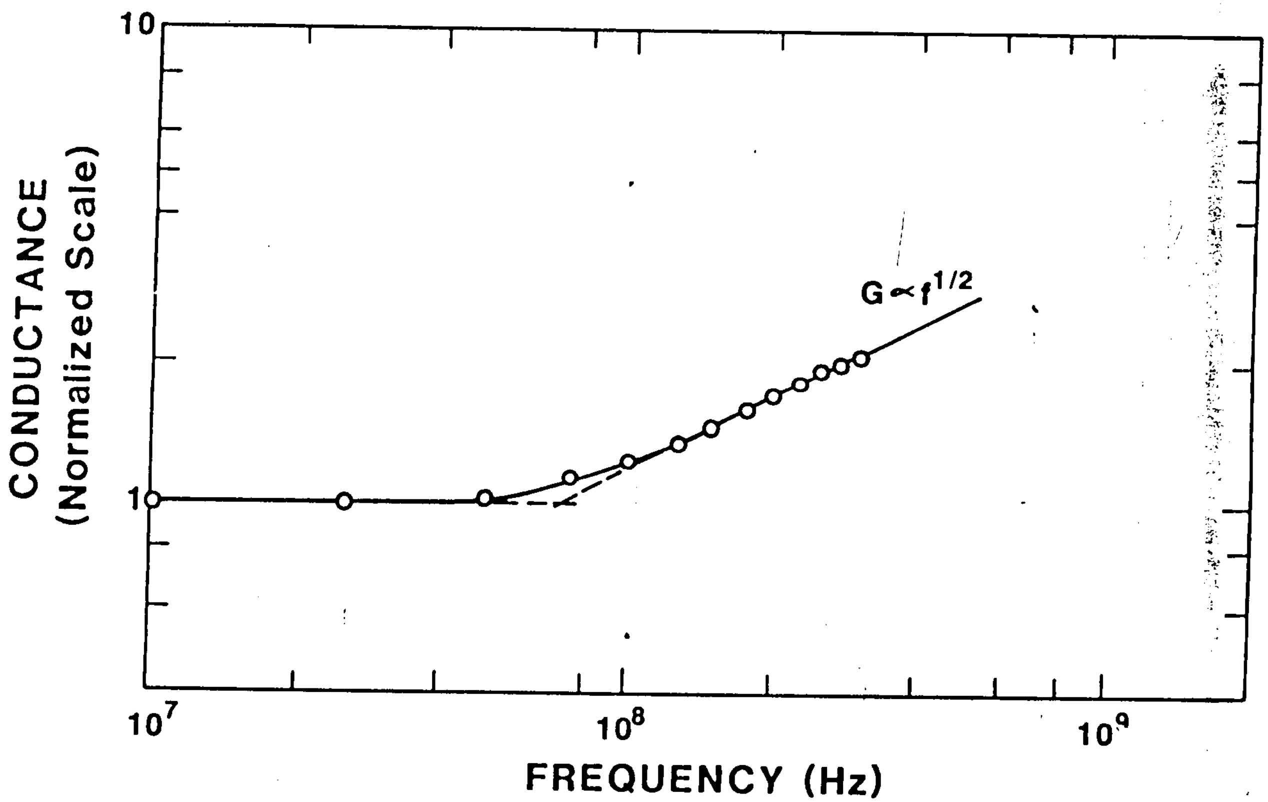
CONDUCTANCE (Normalized Scale)
10
1
$G \propto f^{1/2}$
10^7
10^8
10^9
FREQUENCY (Hz)

Fig. 1

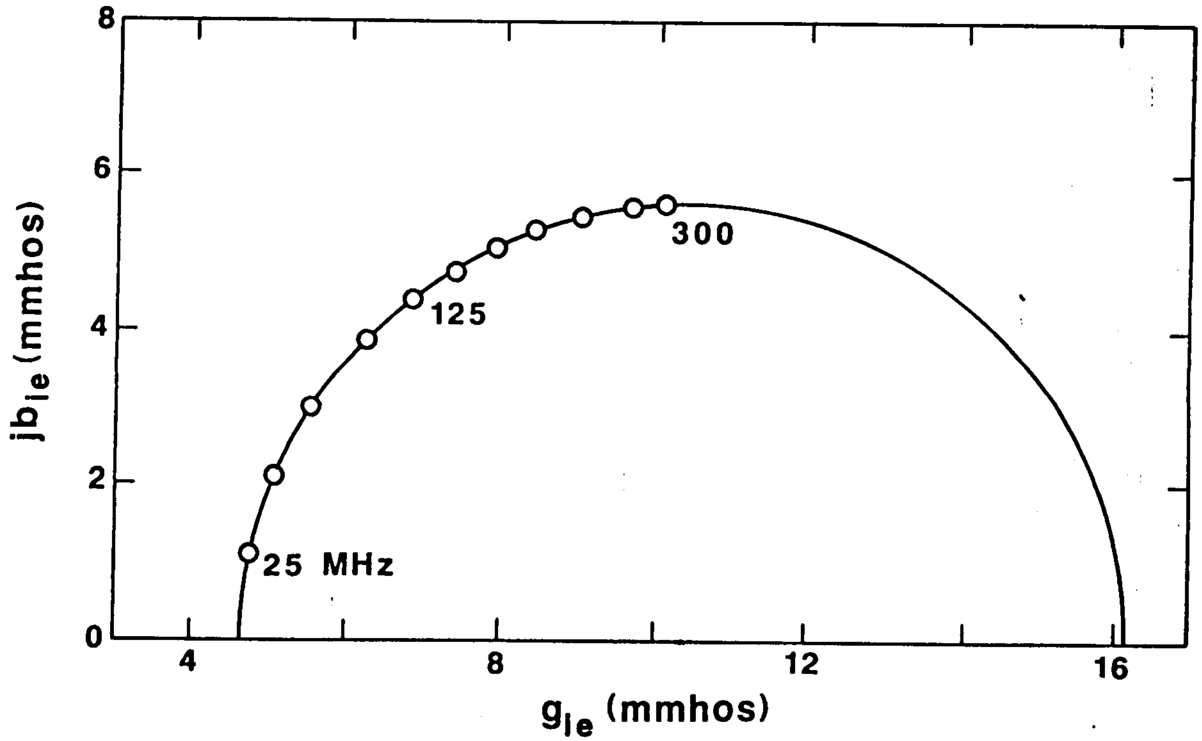

Fig. 2

3. EVIDENCE FOR EXCESS CARRIER STORAGE IN ELECTRON-HOLE PLASMA IN SILICON TRANSISTORS

High-density electron-hole (e-h) plasmas occur frequently in semiconductor device and integrated-circuit applications; examples include plasmas in p/i/n diodes and in the collector regions of bipolar transistors subjected to high currents [1,2]. Among the more recent applications are those involving fast (~ 1 ps) photoconductivity switches [3,4]. Rice and co-workers [5] have reviewed properties of such plasmas at ~ 4 K, where a phase transition leads to e-h droplets and a rigid shift of the conduction and valence band that yields a narrowing of the bandgap. This ΔE_G, resulting from interactions among the carriers contrasts with the ΔE_G occuring in heavily doped semiconductors, where such interactions combine with impurity and band-tail formation to produce the effect. Recently, Abram et al [6] extended many-body theory to include the case of an e-h plasma yielding equivalent results to those of Rice [5] at T = 0 K. The bandgap shrinkage was directly observed between 77 K and 300 K in AlGaAs -GaAs heterojunction lasers [7]. The lasing peak energy was found to be below the nominal material bandgap and increased with increasing carrier concentrations.

In the present paper, using an electrically excited junction device, we present strong experimental evidence for the existence of electron and hole concentrations at $T \approx 300$ K in highly excited Si ($N \approx P > 10^{17}/cm^3$) that markedly exceed N and P predicted traditionally. This excess we then interpret as evidence for ΔE_G in the e-h plasma, and we determine the dependence, $\Delta E_G = f(N,P)$. Finally we indicate implications of these findings for the operation of several semiconductor devices.

In the experiment, we apply a forward voltage V to vary $N \approx P$ and produce the plasma in the low-doped ($N_D \sim 10^{16}/cm^3$) n-type base of a $p^+/n/n^+$ device

(Fig. 1a). To interpret the measured I(V) characteristic for high injection ($N \simeq P \gg N_D$), we assume: (a) the ambipolar diffusion length L greatly exceeds the base thickness W; (b) variations with position x of the electron and hole quasi-Fermi levels across the n-region are small compared with kT; (c) recombination losses in the p^+ and n^+ regions contribute negligibly to the observed current. Thus for the quasineutral base

$$NP \simeq (N_D + \Delta N)\Delta P = n_i^2 \exp[\frac{\Delta E_G}{kT}] \frac{F(\eta_c)F(\eta_v)\exp(eV/kT)}{\exp(\eta_c)\exp(\eta_v)} \qquad (1)$$

$$-(\Delta N + N_o) + (\Delta P + P_o) + N_D = -N + P + N_D \simeq 0 \qquad (2)$$

where Δ means excess density, subscript o means equilibrium, F is the Fermi integral of order 1/2, η_c and η_v are the reduced, normalized quasi-Fermi energies, and n_i is the intrinsic density.

From a procedure outlined below, we can separate from the measured current that component I due to the vanishing of holes and electrons in the quasineutral base:

$$I = Q/\tau = e\int_0^W (1/\tau)\,\Delta N dx = eW\,\Delta N/\tau \quad , \quad \Delta N = \Delta P \qquad (3)$$

where τ is a combination of the transit time and the recombination lifetime, the latter of which is a weak (non-exponential) function of V. For $\Delta E_G = 0$, (1) through (3) yield that the electron and hole density and the current all are proportional to exp(eV/mkT) where m = 1 for low injection and m = 2 for high injection. If, however, $\Delta E_G > 0$ and high injection prevails, then (1) through (3) imply that m = f(V) < 2.

Thus determination of m by experimental observation of $I(V)$ will decide the presence or absence of ΔE_G and its dependence on N and P. For the experiment we used various $n^+/p^+/n/n^+$ microwave transistors. We either shorted the n^+ emitter and subcollector regions or left the n^+ emitter open circuited, with equivalent results. Use of a transistor instead of a diode helped enable separation of the current components, which yielded I of the n-collector (which is the base of the idealized device of Fig. 1). Further separating $I = Q/\tau$ into Q and τ led to the dependence of $\Delta N \approx \Delta P$ on V shown in Fig. 2.

That N and P thus determined markedly exceeds N and P from customary theory (eqs. 1 and 2 with $\Delta E_G = 0$) constitutes <u>indirect proof that $\Delta E_G > 0$ in the e-h plasma</u>. For high injection we see that $m(V)$ is a decreasing function of V, ranging between about 1.4 and 1.1. Further we determine the experimental dependence of ΔE_G on $N = P$. These are the main findings of this paper.

It remains now to fill in details of the experimental procedure that led to the results displayed in Fig. 2.

As a first step in the measurement procedure, we demonstrate that the transistor shown in Fig. 1(c) reduces to the diode structure ($p^+/n/n^+$) of Fig. 1(a). From comparing forward-active and reverse-active measurements of base current and using the base-width modulation technique [8] we determine that the recombination current in the n^+/p^+ emitter and base regions is much smaller than that in the quasineutral (n/n^+) collector. Second, from measuring τ as defined in (3) and the effective surface recombation velocity S near the n/n^+ interface using the method of Ref. 9, we determine $S \ll D/W$, where D is the ambipolar diffusivity: $S < 10^4$ cm/s and $D/W \approx 6 \times 10^4$ cm/s ($W = 2.7$ μm). Using again the method of Ref. 9, we determine that $L > 10$ μm $\gg W$; thus

$$\Delta P(W) \gtrsim \Delta P(0)/[1 + S/(D/W)] \gtrsim 0.85\ \Delta P(0) \quad (4)$$

which means that the excess electron and hole concentrations are nearly x-independent, as illustrated in Fig. 1(b).

The foregoing demonstrates that I in (3) describes the n-collector region for which the n/n^+ junction is characterized by S. Determination of the time constant τ in (3) will thus reveal $\Delta P = \Delta N$ as a function of V, as illustrated in Fig. 2. The measurement of τ was accomplished in two ways. First, from $\tau = Q/I$ for $V \simeq 800$ mV where high injection prevails but where ΔE_G is negligible; variation of V in this range yielded negligible changes in τ. Second, we used the switching technique of Ref. 10. Both methods yielded $\tau \simeq 5 \times 10^{-8}$ s, which is much smaller than the concentration-dependent Auger lifetime [11].

The time constant τ can be much smaller than the recombination lifetime and depends on S. Since S increases with $\Delta N = \Delta P$ for high injection, τ decreases with V until $\Delta N = \Delta P \sim N_{eff} \sim 10^{18}$ cm^{-3}, the doping density of the n^+ substrate corrected for ΔE_G. Thus for $V > 0.8$ V and $\Delta N = \Delta P > 10^{17}$ cm^{-3}, S becomes nearly independent of V : $S \to S_{max} \simeq (D_p/L_p) < 10^4$ cm/s of the n^+ substrate. This was verified by experiment using the method of Ref. [9].

By combining $\Delta N \simeq \Delta P$ with (1), we determine ΔE_G as plotted in Fig. 3. We illustrate the good agreement of our data with transport data [12,13] at $T \simeq 300$ K for heavily doped Si; that our data lies above that for heavily doped Si is expected (see for example Ref. 6) because large numbers of holes and electrons both are present in our experiment. For completeness Fig. 3 includes recent photoluminescent data [14-16] even though the relation between these data (at $T \simeq 5$ K) with ours (at $T \simeq 300$ K) may not be clear because of the effects of lattice vibrations.

We have also studied temperature dependence of the effect in the 77 K-300 K range. Lowering T increases the sensitivity to ΔE_G in the n-region, but it also increases recombination in the n^+ emitter and substrate regions. Thus interpretation for T < 300 K becomes more difficult. The preliminary results indicate that ΔE_G decreases with decreasing T.

To complete our analysis, we reconsider the approximations (a) through (c) underlying our interpretation. The preceding discussion has already justified (a) and (c). An upper bound for the variation with x of the electron and hole quasi-Fermi levels is determined from the total current which provides an upper bound on the two particle currents. The slope of the quasi-Fermi levels is less than $I/\mu N$ or $I/\mu P$, which is about 1 mV/μm for standard values of mobilities for $N_D \approx 10^{16}$ cm^{-3}; this gives a change of less than 3 mV (<< kT/e) across the conductivity modulated n-region.

This implies that the variation of the electric potential across the n-region is negligible, but does not rule out the influence of other resistance drops such as those at the contacts. A correction for small IR drops was accomplished using a method first proposed by Giaccolletto [17].

The fact that a sizable ΔE_G exists at plasma densities ~ 10^{18} cm^{-3} has important device implications. Such densities occur in p/i/n devices and in switching bipolar transistors operating at biases larger than about 0.8 V. For switching transistors the implication is that a low-doped collector stores a significantly larger amount of charge than conventionally thought. The e-h plasma effects are also important in the space-charge-region of a p/n junction under high forward voltage where huge quantities of both electrons and holes are present. The presence of bandgap shrinkage may modify the analysis of mechanisms underlying current-induced base widening in bipolar transistors [18,19]. It can play a role in determining the conversion efficiency of solar cells under highly concentrated illumination.

In this short note we have presented evidence for significantly greater hole and electron charge in an electron-hole plasma at room temperature than conventional theory would predict. Interpreted as resulting from bandgap narrowing, this extra charge gives values of ΔE_G that are somewhat greater than those observed from photoluminescence and transport data on heavily doped Si.

SECTION 3 REFERENCES

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SECTION 3 FIGURE CAPTIONS

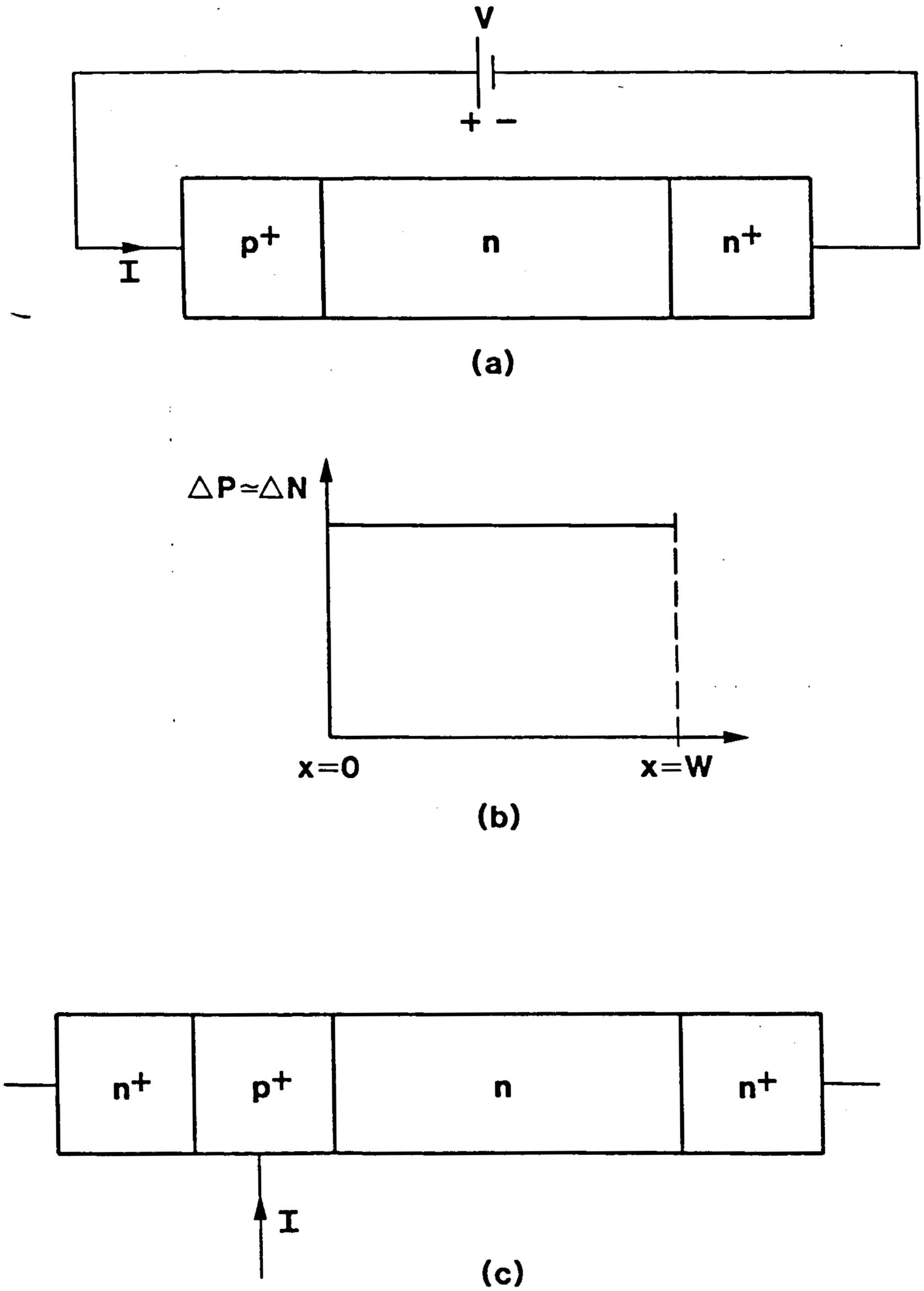
Fig. 1 (a) Schematic illustration of a $p^+/n/n^+$ structure used for the analysis.

(b) Profile of excess charges in the n-type base.

(c) Schematic illustration of the $n^+/p^+/n/n^+$ transistor used in experiments.

Fig. 2 The excess charge $\Delta P \approx \Delta N$ in the n-region of the transistor of Fig. 1(c) versus the voltage V applied to the p^+/n junction. The solid line is the theoretical dependence for $\Delta E_G = 0$. The circles are the measured points (T = 298 K) obtained from the measured current I using (3).

Fig. 3 Bandgap narrowing as a function of the electron or hole concentration. The open circles are the results of this work for the e-h plasma at T = 298 K; , Δ, , Δ are the photoluminesce data at $T \approx 4$ K for the n^+ and p^+ heavily doped Si; + and * are the transport data at $T \approx 300$ K for p^+ and n^+ Si.



Neugroschel et.al. FIG. 1

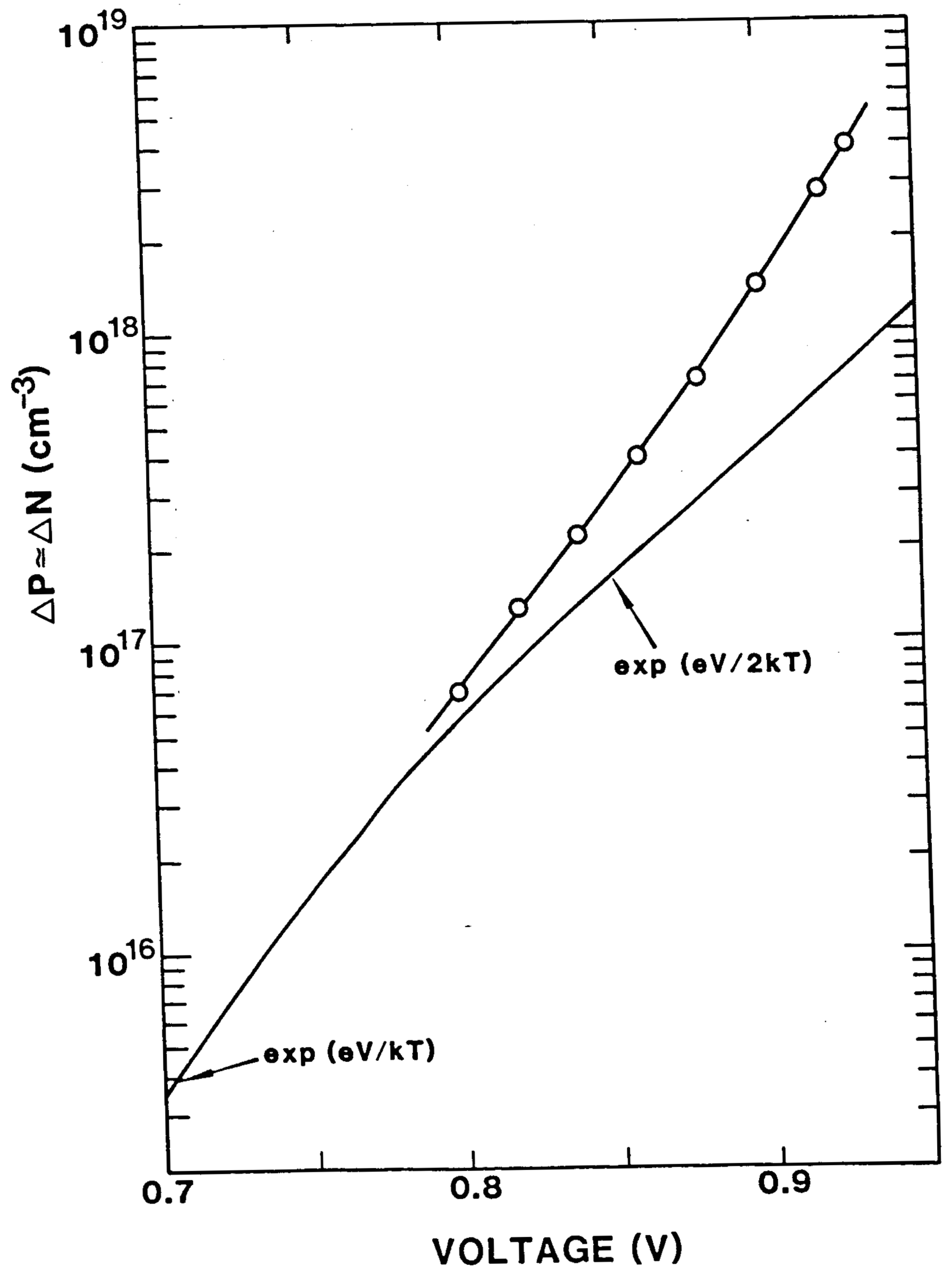


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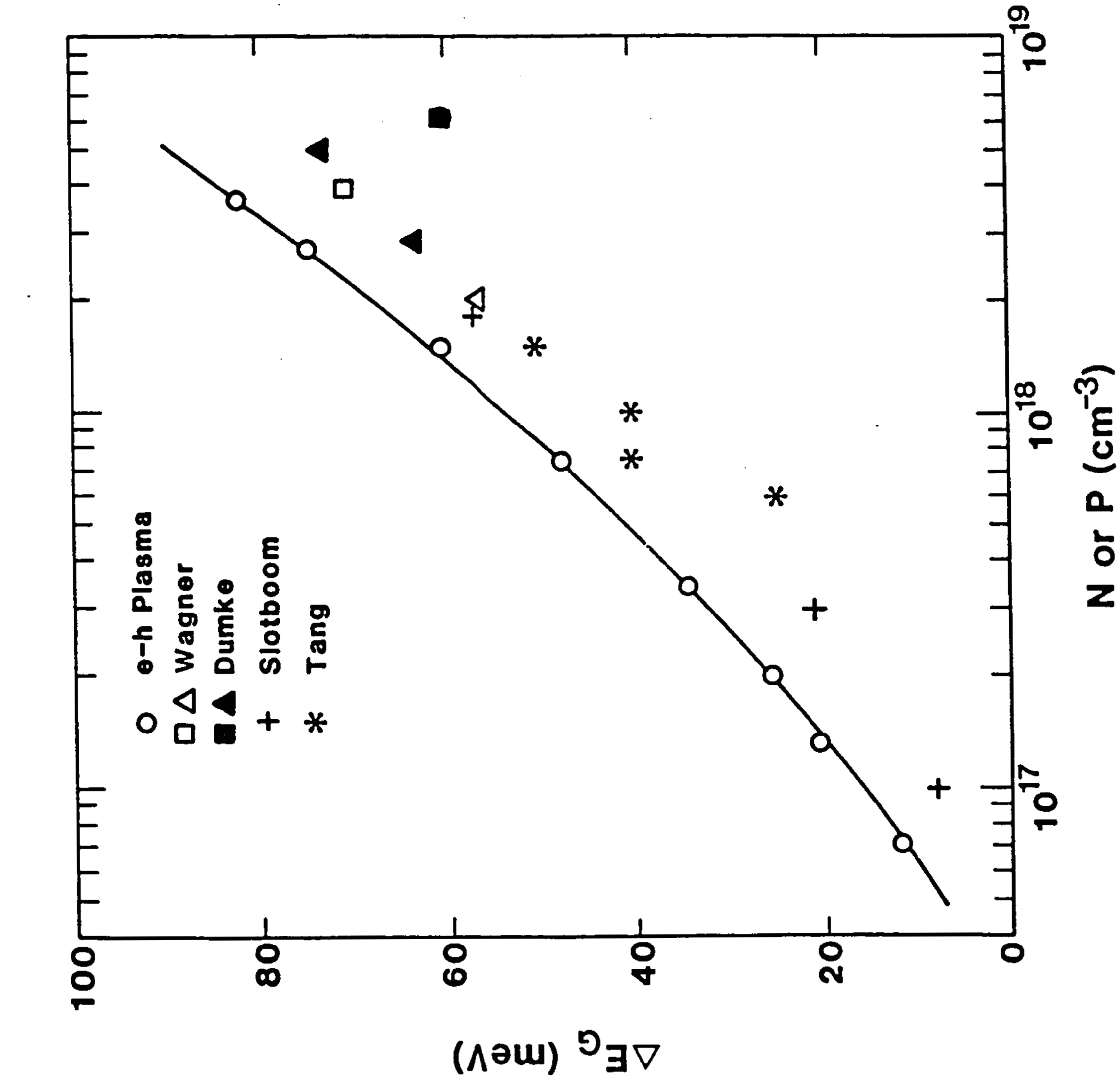
FIG. 2



e-h Plasma
Wagner
Dumke
Slotboom
Tang
ΔE_G (meV)
0
20
40
60
80
100
N or P (cm^{-3})
10^{17}
10^{18}
10^{19}