A New Model of Negative Photoconduction

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Abstract

A one-deep-level impurity, space-charge neutral and steady-state model is proposed and verified in n-Si samples, overcompensated but not inverted by gold acceptors. The physics is as follows. If the photo-ionization rate of trapped holes at the impurity center is greater than electrons, then an extrinsic monochromatic illumination will increase the trapped electron concentration. To maintain quasi-neutrality and a constant steady state trapped electron concentration (equal to that of the shallow level donor), the injected electron concentration into the compensated n-region must decrease, thus, decreasing the electron or total current since hole concentration is so low and even lower in the presence of a swept-out electric field that its contribution is negligible. This model has sucessfully predicted the observed large NPC (three times or more reduction of dark current), the high intrinsic optical gain (~50) and the sublinearity in dark current.

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I. Introduction

Negative photoconductivity or photocurrent (NPC) have been reported in many amorphous materials.[1,2] Well defined NPC was first observed by Stockmann[3,4] in electron irradiated Ge. There have been renewed interests on this effect with experimental observations in n-type semiconductors: gold-doped Ge[5], cobalt-doped Si[6] and gold-doped Si[7]. The interpretation of the experimental results has been qualitative and based on Stockmann's two-level impurity model[4]. In this model, very special conditions on the thermal capture cross-sections of minority carriers are required.[2] Because of the small magnitude observed, the NPC effect was thought to be a different mechanism than that which gives large intrinsic photoconduction and optical gain.

This paper shows that the observed extrinsic NPC, high intrinsic optical gain and its associated sublinear dark current can all be completely accounted for by a one deep-level impurity model in an applied electric field. In contrast to Stockmann's equilibrium model, the new model shows that NPC ceases when the applied electric field is removed due to the ~~lack of a swept-out depletion~~ presence of a sufficient number of minority carriers.

II. Physics of the Model

Consider a N+IN+ structure under an applied voltage V whose energy band diagram is shown in Fig. 1. The shallow-level donor in the I-region (donor concentration N_D) is overcompensated but not inverted by a deep-level acceptor impurity ($N_{TT} > N_D \sim 10^{15}$ donors/cm^3) so that the I-region is still N-type and $N \gg P$. Thus, the conduction is dominated by electron drifting from the left N+ region through the I region. Below about 10^5 V/cm so that space charge is not important, electrical neutrality is maintained over the entire I region except the small end region near the cathode(left N+ region) which can be neglected. Thus, almost all the excess electrons from the shallow donors are trapped at the deep acceptors, i.e. N_T(trapped electron concentration)=N_D shallow donors/cm^3 and the electron concentration, N, is very small: $N<<N_T=N_D$. One of the most important point of this model is that the condition of constant trapped electron concentration will persist under illumination if $N_D>10^{15}/cm^3$ since for practical light intensities ($\Phi<10^{16}$ photons/cm^2-s) the photoelectron concentration will satisfy $N<<N_D=N_T$.

When the sample is exposed to an extrinsic monochromatic light, trapped electrons (N_T) and holes ($P_T=N_{TT}-N_T$) are released. If the photoionization rate of trapped holes (shown as e_p^o in Fig. 1) is greater than electrons (e_n^o), then the trapped electron concentration would increase which is not possible since $N_T=N_D$=constant. Thus, the increase of the rate due to e_p^o over e_n^o must be balanced by a decrease of the thermal capture rate of electrons (shown as c_n^tN in Fig. 1). This would decrease the injected electron concentration N and reduce the total conduction current, giving negative photocurrent.

The neglected hole (minority) contribution, which is positive under illumination, is small due to the low concentration of holes present in the I region (P<<N). However, ~~a very small amount of hole swept out or depletion in the I region is necessary for NPC~~ and the presence of holes will set the lower limit on the ~~sweep~~ applied electric field below which the positive hole contribution will mask the NPC.

III. Mathematical Solution

The solution can be readily obtained from the physical model just discussed and the simple solution neglecting holes will be given first. Electrical neutrality in the I region gives $0=P-N+N_D-N_T \simeq N_D-N_T$ when the total deep level concentration N_{TT} is greater than the shallow level donor concentration N_D and when $N_D>10^{15}/cm^3$. The trapped electron concentration can be obtained from the steady state balance of the six rate processes shown in Fig. 1, giving $c_n^t NP_T-(e_n^t+e_n^o)N_T=c_p^t PN_T-(e_p^t+e_p^o)P_T$ so that

$$c_n^t N = (N_T/P_T)(e_n^t+e_n^o+c_p^t P) - (e_p^t+e_p^o) \tag{1}$$

$$= [N_D/(N_{TT}-N_D)](e_n^t+e_n^o) - (e_p^t+e_p^o) \tag{1A}$$

where in (1A) use is made of $P<<N<<N_D \simeq N_T = N_{TT}-P_T$. The photoelectron concentration in the I region is then

$$c_n^t \Delta N = [N_D/(N_{TT}-N_D)]e_n^o - e_p^o \tag{2}$$

which is negative and gives NPC if $e_p^o/e_n^o > [N_D/(N_{TT}-N_D)]$. This is possible for the overcompensated but still N-type I region where $N_{TT}>N_D$ and for the gold acceptor level located 0.545 eV below the Si conduction band gap which has $e_p^o/e_n^o>1$ in the extrinsic range of $\hbar\omega$ > 670 mV.[8/] However, the inequality for NPC can still be satisfied even if $e_p^o/e_n^o < 1$ provided that $N_{TT}>>N_D$.

In the next section, (2) is tested experimentally and found to give excellent result.

To establish the low electric field limit for NPC, the positive hole contributions must be included in the solution. This is most evident in (1) and the hole capture term, $c_p^t P$, when included in (2) will reduce the negative photoelectron concentration.

The hole concentration can be ~~obtained~~ estimated from the steady state balance between hole recombination at the deep level and the drift rate of holes ~~swept out by~~ in the electric field across the I region, giving

$$P/t_{tr} = (e_p^t+e_p^o)(N_{TT}-N_T) - c_p^t P N_T \qquad (3)$$

where $t_{tr}=L/\mu_p E$ is the hole transit time across the I region.

The hole and electron concentrations in the charge neutrality condition, $P-N+N_D-N_T=0$, may still be neglected as long as $N_{TT}>N_D=N_T>>N>>P$ which is valid in practice as we have just discussed. Using $N_D=N_T$, the hole concentration from (3) is given by

$$c_p^t P = (e_p^t+e_p^o)[(N_{TT}/N_D)-1]/[1+(\tau_p/t_{tr})] \qquad (4)$$

and the electron concentration from (1) and (4) is then

$$c_n^t N = [N_D/(N_{TT}-N_D)](e_n^t+e_n^o) - \{(\tau_p/t_{tr})/[1+(\tau_p/t_{tr})]\}(c_n^t/c_p^t)(e_p^t+e_p^o) \qquad (5)$$

where $\tau_p=1/c_p^t N_D$ is the hole lifetime in the I region.

These results are also valid at thermal equilibrium $E=0$, since (3) is valid. They show that the thermal equilibrium electron and hole concentrations would increase with illumination, e_n^o and e_p^o, and no negative photoeffect would be expected.

The minimum electric field required for NPC can be obtained from the photocurrent inequality $\Delta J=q(\mu_n\Delta N+\mu_p\Delta P)E \le 0$. Making use of (4) and (5), the oneset condition for NPC is then

$$\tau_p/t_{tr} = \mu_p E/Lc_p^t N_D$$

$$\ge \{1+(e_p^o/e_n^o)(\mu_p/\mu_n)(c_n^t/c_p^t)[(N_{TT}/N_D)-1]^2\}/\{(e_p^o/e_n^o)[(N_{TT}/N_D)-1]-1\} \qquad (6)$$

The second term in the numerator comes from the positive photohole current with is small compared with 1 at the gold acceptor level in Si where $c_n^t \ll c_p^t$.

A simplier analysis of the threshold condition can be made for this case which requires that $\Delta N<0$ since the positive photohole current can be neglected. From the steady-state balance of the six processes indicated in Fig. 1, we have then $c_n^t P_T \Delta N = e_n^o N_T + c_p^t N_T \Delta P - e_p^o P_T < 0$. Thus, $c_p^t N_T \Delta P < e_p^o P_T - e_n^o N_T$ which states that for NPC, the thermal capture rate of photoholes must be smaller than the photogeneration rate of holes over electrons. This can be reduced into a slightly different form using (3) to give $\Delta(P/t_{tr}) > e_n^o N_T$. which states that for NPC, the drift rate of photoholes must be faster than photoelectron generation rate.

The threshold condition of the applied voltage for NPC can be obtained from either of the two inequalities just obtained by eliminating P from (3), giving

$$[t_{tr}^{-1}/(\tau_p^{-1} + t_{tr}^{-1})] e_p^o P_T > e_n^o N_T \qquad (6A)$$

which is identical to the complete form given by (6) with the photohole current term (second term in the numerator) neglected. It also reduces to the condition following (2) if $t_{tr} \ll \tau_p$ or hole contribution is completely neglected at high fields. The result given by (6A) is intuitively simple: it states that when hole contribution is important, NPC can occur only when the photogeneration rate of hole $e_p^o P_T$, reduced by the probability of hole drift relative to thermal hole capture $[t_{tr}^{-1}/(\tau_p^{-1} + t_{tr}^{-1})]$, must be greater than photoelectron generation rate, $e_n^o N_T$.

The minimum electric field required by (6) is quite low and could be thought of as a thermal equilibrium process mistakenly. A numerical estimate can be made for the gold acceptor in Si where $c_n^t/c_p^t=1.65\times10^{-9}\div 1.15\times10^{-7}=0.014$ [9] and $e_p^o/e_n^o\sim10$. Let $N_{TT}(Au)=2N_D=2\times10^{16}/cm^3$ and $\mu_p/\mu_n=330/1000$, then from (6), we have $\tau_p/t_{tr}=\mu_pE/Lc_p^tN_D>[N_D/(N_{TT}-N_D)](e_n^o/e_p^o)\approx0.1$ so that $E(V/cm)>40L(\mu M)$. This example shows that the hole transit time needs not be small compared with the hole lifetime in order to get NPC and that NPC can be expected at rather low electric fields. For example, let $L=25\mu M$, then $V=EL>2.5$ volts. *our samples give 0.5 volt threshold.*

The effect of space charge on the reduction of the NPC can be estimated from the approximation $\epsilon dE/dx\approx-\epsilon E/L\approx\epsilon V^2/L=q(P-N+N_D-N_T)\approx q(N_D-N_T)$. This shows that N_D in (4) and (5) is to be replaced by $N_D+\epsilon E/qL$. Thus, an increase in space charge or electric field would reduce the total negative ΔN. However, for $N_D=10^{16}/cm^3$, space charge effect becomes important only when $\epsilon E/qL=N_D$ or $E=4\times10^6V/cm$ for $L=25\mu M$. Thus, there is a wide range of applied voltage (2.5 to 10^4 volts for this example) where NPC appears and space charge effect is negligible.

The negative photocurrent due to the gold donor level (E_V+345 mV) in Si in the Stockmann two-level model can be shown to be negligibly small compared with the contribution from the model just presented. To estimate this contribution, we note that most of the gold donors are in the neutral state in the I region and its concentration is $N_{TT}-N_D$. The recombination rate at the donor level is then limited by hole capture whose rate is $c_{p0}^tP(N_{TT}-N_D)$. This must be added to the hole capture term at the acceptor level, $c_p^tPN_T$, in (3) and would increase this term by $(c^t_{p0}/c^t_p)(N_{TT}-N_D)/N_D \sim (c^t_{p0}/c^t_p)=2.4\times10^{-8}/1.15\times10^{-7}=0.2$. The reduction of the electron concentration due to recombination at the gold donor level (Stockmann's effect) is also negligible since the electron capture rate into the gold acceptor level is considerably larger than into the unoccupied donor level. This ratio is $c^t_n N(N_{TT}-N_D)/(c^t_{n-1} NN_{Au+})$ $=c^t_n N(N_{TT}-N_D)/[c^t_{n-1}N(c^t_{p0}P+e_{n0})/(c^t_{n-1}N+e_{p-1})]=(c^t_n/c^t_{n-1})(c^t_{n-1}N+e_{p-1})/c^t_{p0}P$ $\approx 10^5$ using the numerical values listed in references 8, 9 and 10.

IV. Experimental Results

Experimental verification of the new model has been made on gold diffused silicon N+IN+ diode structures with the following parameters: $N_D=10^{15}/cm^3$, $N_{TT}(Au)=2$ to $5\times10^{15}/cm^3$, L=12μM, N+ layer thickness=5μM and area=0.0045 cm^2. A comparison between the theory and experiment on the spectral response of the photocurrent is shown in Fig. 2 both in the extrinsic NPC range (labeled (-)) and the positive intrinsic photocurrent range (labeled (+)). The dark current at the 202°K sample temperature is 15.5 nA while the NPC peaks at about 10 nA. The left scale gives the optical gain, showing that a value of 20 is both predicted and observed in this sample. The maximum intrinsic optical gain is about 50 and the reduction to 20 in this sample is due to the absorption in the top N+ layer of 5μM thickness.

Data correlating the NPC threshold condition given by (6), temperature and field dependences of the sublinear dark current and transient response are obtained and will be published elsewhere.

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Footnotes

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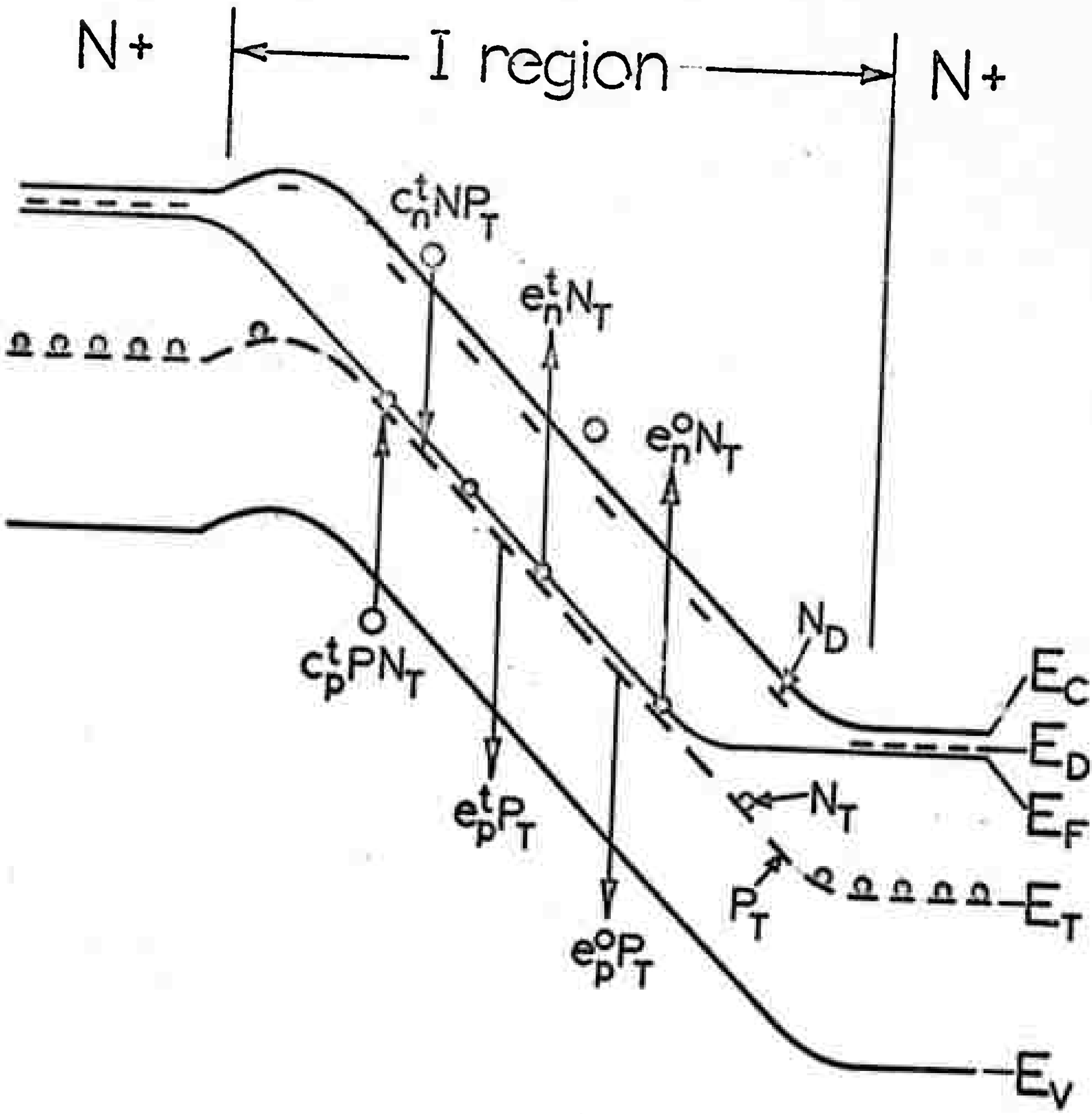
Figure Captions

1. The energy band diagram of a N+IN+ diode structure. The I region is doped with a shallow donor of concentration N_D and over-compensated by a deep level acceptor with concentration N_{TT} and energy level E_T. N_T and $P_T=N_{TT}-N_T$ are the trapped electron and hole concentrations at the deep acceptor level. The six vertical arrows indicate the four thermal capture and emission processes and the two photoionization processes of electrons and holes under extrinsic illumination. The rates of the six processes are shown as $c_n^t NP_T$, etc.

2. Comparison of theory with experimental photocurrent spectra taken on a gold doped silicon N+IN+ diode at 202°K and 10 volts bias. The theory is calculated from (4) and (5) using the data given in references 8, 9 and 10. (-) is the negative extrinsic photocurrent region while (+) is the positive intrinsic photocurrent region.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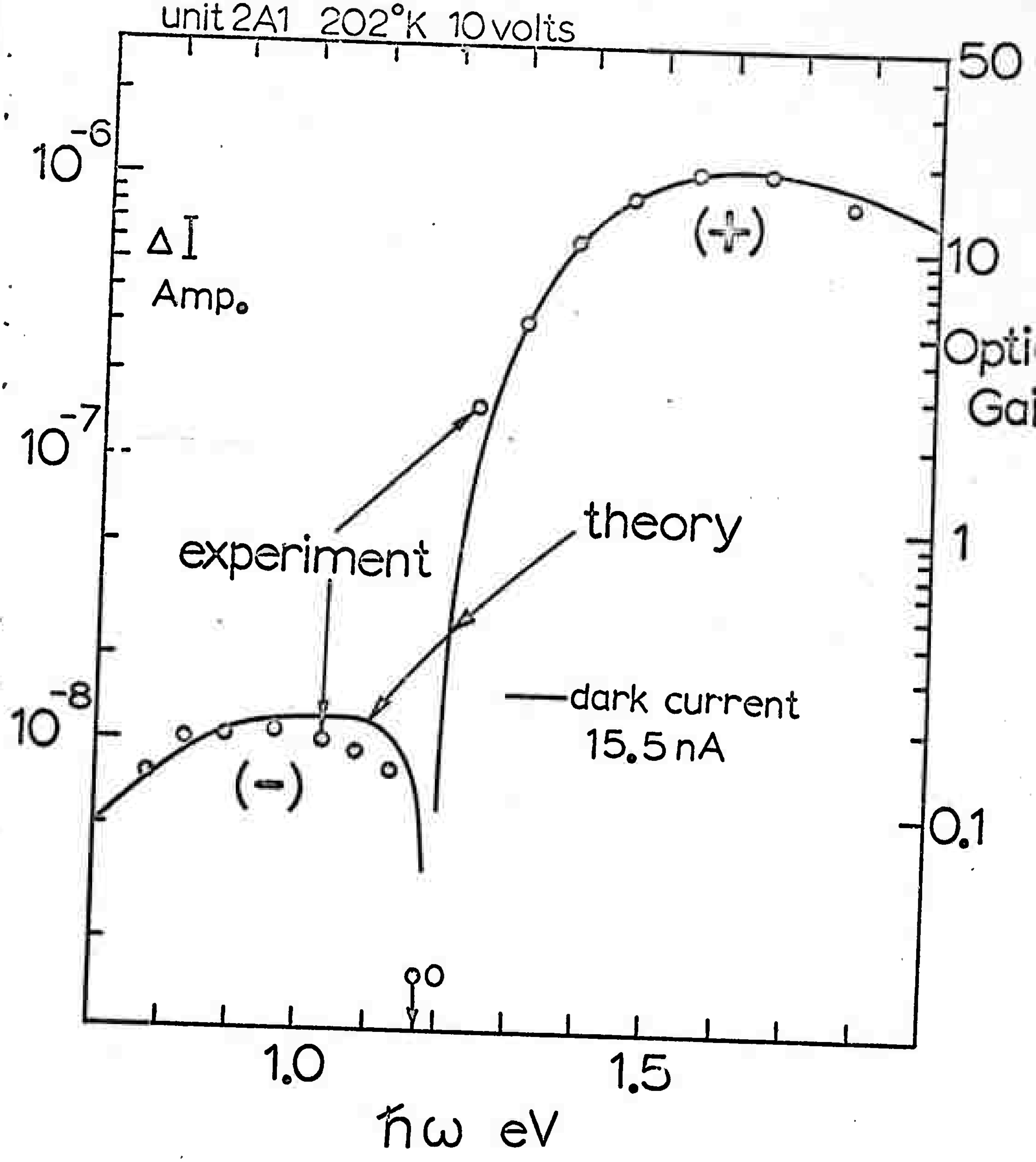
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