ing V_{FB} experimentally from the observed photocurrent-bias curves, and in part to the difficulty in estimating the terms χ and V in Eq. (1) accurately. However, the disagreements are sufficiently large to make doubtful the validity of Eq. (1) for the materials reported here.

For practical applications long-term stability is required. Preliminary results show that $CdIn_2O_4$ and Cd_2GeO_4 produce stable photocurrents over a period of 100 h. However, the efficiency of Cd_2SnO_4 decreases drastically after 4 h of intense illumination, probably due to decomposition of the material. For application in solar-driven photoelectrolysis cells one requires,[1] in addition to stability, a large efficiency for photons of $h\nu < 3$ eV. Moreover, in order to dispense with the need for an external bias, V_{FB} should be sufficiently negative. From the data presented here we conclude that none of these oxides has the combination of small band gap, large negative flat-band potential, and chemical stability necessary for solar energy applications.

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$In_{0.53}Ga_{0.47}As$ photodiodes with dark current limited by generation-recombination and tunneling

S. R. Forrest
Bell Laboratories, Murray Hill, New Jersey 07974

R. F. Leheny, R. E. Nahory, and M. A. Pollack
Bell Laboratories, Holmdel, New Jersey 07733

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We report on low dark-current $In_{0.53}Ga_{0.47}As$ photodiodes in which generation-recombination current dominates diode leakage up to as high as 100 V. At higher voltages, tunneling currents become dominant, resulting in the soft breakdown characteristic widely observed in these materials. The dark current versus voltage characteristics have been fit to variations in current of over six orders of magnitude and a temperature range greater than 150 K using a theory which includes generation-recombination, tunneling, and shunt components.

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Recently, considerable interest has been shown in the alloy system $In_xGa_{1-x}As_yP_{1-y}$ for use as photodetector material in long-wavelength (1.2–1.6 μm) light-wave communication systems. Photodiodes made from these materials have been beset by anomalously large dark currents which increase nearly exponentially with applied voltage.[1-4] The excess dark current has been attributed to several different sources—for example, surface conduction,[5] microplasmas,[4,6] and, more recently, to tunneling.[7] In this letter we report on $In_{0.53}Ga_{0.47}As$ photodiodes with reverse current characteristics which can be remarkably well fit to a wide range of applied voltages and temperatures using a theory that takes account only of currents originating from tunneling, generation-recombination, and shunt components. These results, obtained for diodes exhibiting near-ideal dark-current–voltage characteristics, establish that it is tunneling currents that determine the high-voltage response for these materials.

The $In_{0.53}Ga_{0.47}As$ diodes studied consist of grown p-n junctions prepared by liquid phase epitaxy on ⟨100⟩ InP:Sn substrates. The undoped n layer was grown on an InP buffer layer to a thickness of 10 μm. Next a 2-μm-thick, heavily Zn-doped p layer was grown, forming an abrupt junction. Mesas were etched, and a window in the p-surface contact permitted photoexcitation. Measurements were made on two sets of diodes having n-layer carrier concentrations of $N_D = 1.1\times10^{15}$ cm^{-3} (sample A) and $N_D = 1.5\times10^{16}$ cm^{-3} (sample B). The carrier concentration was quite uniform, varying by $\lesssim 10\%$ over the region measured. In each case, six diodes having similar electrical characteristics typical of the best 30% of the approximately 100 diodes available per wafer were studied. In Fig. 1 we show the current-voltage (I-V) characteristics for the two samples (measured data are indicated by dots). There is a gradual increase in dark current with voltage up to ~ 100 V for sample A and ~ 20 V for sample B for the room-temperature ($T = 285$ K) characteristics. With a further increase in voltage, the current increase becomes nearly exponential.

On reducing the area of sample A from 1.5×10^{-4} to 1.4×10^{-5} cm^2 by etching, the current at 138 V dropped from 28 to 3 μA, and the current at 2 V was reduced from 75 to 4 nA. This indicates that the current is proportional to

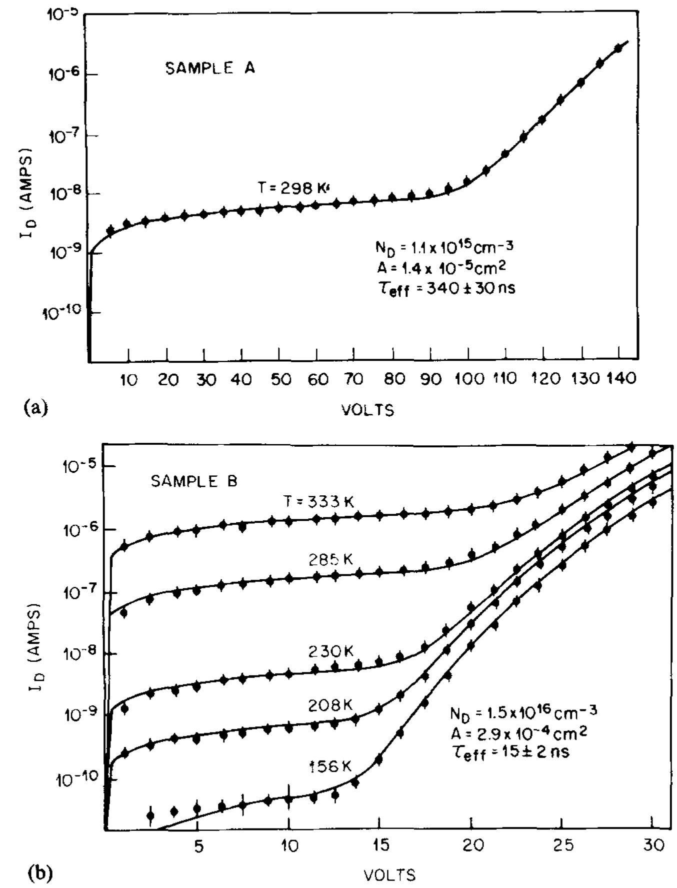

FIG. 1. (a) Measured (dots) and theoretical (lines) current-voltage characteristics for sample A at $T = 298$ K (b) Measured (dots) and theoretical (lines) current-voltage characteristics for sample B at several temperatures.

junction area at both low and high voltage. We conclude, therefore, that the current originates in the semiconductor bulk, eliminating the surface as a major source of leakage.[8]

This observed dark-current response can be quantitatively described by the sum of three independent current sources: generation-recombination (G-R) via traps in the depletion region, tunneling of carriers across the band gap, and a shunt resistance R_s across the junction.

The G-R current, which is dominant at low voltage, is given by the well-known relationship[9]

$$I_{G\text{-}R} \cong (qn_i AW/\tau_{\rm eff})[1 - \exp(-qV/2kT)] , \qquad (1)$$

where q is the electron charge, k is Boltzmann's constant, n_i is the intrinsic carrier concentration, $\tau_{\rm eff}$ is the effective carrier lifetime, and W is the depletion region width, which for abrupt junctions is $W = [2\kappa_s(V + V_{\rm BI})qN_D]^{1/2}$. Here V is the applied voltage (taken as positive under reverse bias), $V_{\rm BI}$ is the built-in voltage, and κ_s is the dielectric constant ($\kappa_s = 1.06$ pF/cm). The term in parentheses in Eq. (1) is applicable for generation and recombination of carriers via midband traps.

Tunneling dominates the dark current at high voltages, and is given for direct-gap semiconductors by the expression[7,10]

$$I_{\rm tun} \cong \gamma A \exp[-\theta m_0^{1/2}\epsilon_g^{3/2}/q\hbar E_m] , \qquad (2)$$

where m_0 is the free-electron mass, E_m the maximum junction electric field given by $E_m = 2(V + V_{\rm BI})/W$, $\hbar$ is Planck's constant divided by 2π, and ϵ_g is the energy gap. The parameter θ is given by[7] $\theta = \alpha(m^*/m_0)^{1/2}$, where m^* is the electron effective mass and α, which depends on the detailed shape of the tunneling barrier, is on the order of unity for band-to-band processes. Finally, the prefactor γ depends on the initial and final states of the tunneling carrier; for band-to-band tunneling, $\gamma = (2m^*/\epsilon_g)^{1/2} q^3 E_m V/4\pi^2\hbar^2$. For tunneling via traps in the band gap, γ would take a somewhat different form,[10] and would depend on trap density.

Finally, the shunt current is given by

$$I_s = V/R_s . \qquad (3)$$

Junction breakdown and avalanche current multiplication might be expected at high voltage. However, since no avalanche gain was observed in the diode photoresponse over the voltage range investigated, this contribution has been omitted in the dark-current analysis.

We have tested the assumption that Eqs. (1)–(3) completely describe the diode response by investigating the temperature variation of the measured dark current. For the G-R current, the temperature variation is given by[9] $I_{G\text{-}R} \propto n_i/\tau_{\rm eff} \propto \exp[-\epsilon_g(T)/nkT]$, where the factor $n = 2$ for the special case of generation and recombination via midband traps. For the tunneling current, variation with temperature is determined by variation in $\epsilon_g^{3/2}(T)$ [Eq. (2)]. The temperature dependence of R_s, which is $\approx 10^{11}\,\Omega$, has been neglected since I_s is significant only at low temperatures for sample B, and is negligible for sample A.

The variation of the energy gap with temperature was obtained by measuring the diode photoresponse as a function of wavelength and temperature. These results can be approximated by $\epsilon_g(T) = \epsilon_g(0) - \sigma T$ to $\pm 0.5\%$ over the range $90 \leqslant T \leqslant 400$ K. Values of $\epsilon_g(0)$ and σ, along with other physical parameters for samples A and B are given in Table I.

In Fig. 2 the dark current at low voltage is plotted versus ϵ_g/T for samples A and B. From these data, we find $I_{G\text{-}R} \propto \exp(-\epsilon_g/nkT)$, where $n = 1.8 \pm 0.1$ for sample A and $n = 2.2 \pm 0.1$ for sample B, indicating that generation and recombination indeed occurs via traps near the middle of the band gap.

Summing these three current terms, and using the temperature variation results, we have fit the I-V characteristics for samples A and B to obtain the results indicated by solid lines in Fig. 1. Values of the parameters $\tau_{\rm eff}$, θ, and R_s derived from this fitting procedure are given in Table I.

The excellent fit to the measured diode characteristics indicates that the three sources of dark current considered fully describe diode behavior. On this basis, we can draw several conclusions concerning the factors that affect diode performance. First, the effective carrier lifetime $\tau_{\rm eff}$ increases with decreasing doping density—a result consistent with a previous analysis of measurements in III-V semiconductors.[7] Since carrier lifetime is inversely proportional to the trap density,[9] this result suggests that the trap density is a function of the density of dopant atoms. Second, with $\theta = \alpha(m^*/m_0)^{1/2} = 0.30$ for both samples, and[12] $m^*/m_0 = \sim 0.04$ for $In_{0.53}Ga_{0.47}As$, we find $\alpha = 1.6$. This

TABLE I. Properties of $In_{0.53}Ga_{0.47}As$ photodiodes.

Parameter	Symbol	Sample A	Sample B
Intrinsic carrier concentration[a] at $T = 300$ K	n_i (cm^{-3})	1.1×10^{12}	9.6×10^{11}
Energy gap at $T = 0$ K	$\epsilon_g(0)$ (eV)	0.821 ± 0.003	0.823 ± 0.003
Energy-gap temperature coefficient	σ (eV/K)	$(3.20 \pm 0.02)\times10^{-4}$	$(2.99 \pm 0.01)\times10^{-4}$
Doping density	N_D (cm^{-3})	1.1×10^{15}	1.5×10^{16}
Area	A (cm^2)	1.4×10^{-5}	2.9×10^{-4}
Capacitance[b]	C (pF)	0.04	3.0
Built-in voltage	V_{BI} (V)	-0.49	-0.47
Effective lifetime at $T = 300$ K	τ_{eff} (ns)	340 ± 30	15 ± 2
Tunneling parameter	θ	0.30 ± 0.02	0.30 ± 0.01
Shunt resistance	R_s (Ω)	$< 10^{10}$	2.3×10^{11}

[a]$n_i = (N_cN_v)^{1/2}e^{-\epsilon_g/2kT}$, where $(N_cN_v)^{1/2} \approx 10^{18}$ cm^{-3} (Ref. 9).

[b]Capacitance values, measured at $V = 0$ V, correspond to diode areas given above.

value lies between $\alpha = 1.11$ for band-to-band tunneling through a triangular barrier, and $\alpha = 1.88$ for band-to-band tunneling through a parabolic barrier.[9] Finally, the parameter γ differs from the value expected for band-to-band tunneling by roughly a factor of 40 for the two samples. However, owing to the strong dependence of I_{tun} on θ, small variations in θ result in large variations in γ. Thus, although γ is in rough agreement with band-to-band tunneling, the possibility that tunneling occurs via a few mid-band-gap traps is not precluded.[11,13]

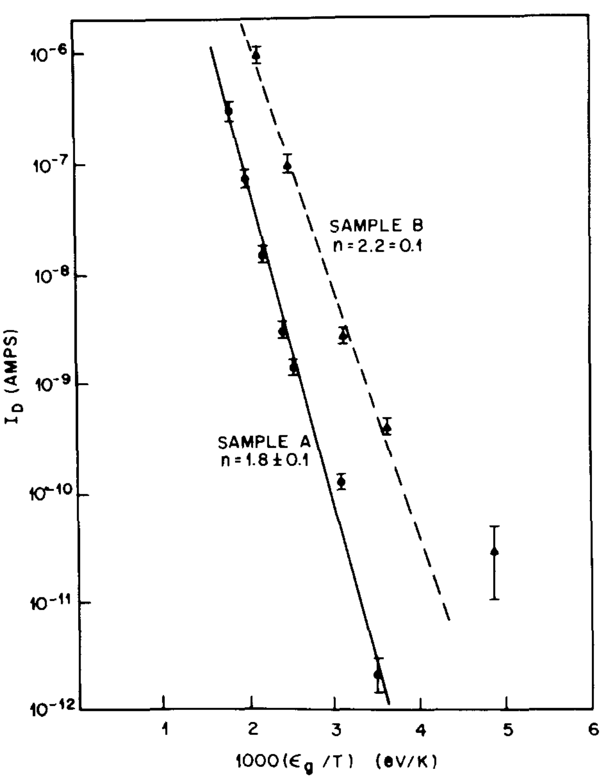

FIG. 2. Dark current I_D vs ϵ_g/T at $V = 5$ V for sample A (dots) and sample B (triangles). Both samples follow $I_D \propto \exp(-\epsilon_g/nkT)$, where $n = 1.8 \pm 0.1$ and $n = 2.2 \pm 0.1$ for samples A and B, respectively.

In conclusion, we have analyzed in detail the dependence of reverse-biased leakage current on both voltage and temperature for $In_{0.53}Ga_{0.47}As$ photodiodes exhibiting near-ideal dark-current-voltage characteristics. We find that the I-V characteristics can be remarkably well fit to current variations of over six orders of magnitude using a model where the dark current consists only of generation-recombination, tunneling, and small shunt components. Our results, which are consistent with a previous study[7] on several III-V compounds including $In_xGa_{1-x}As_yP_{1-y}$, indicate that it may be difficult to make sensitive avalanche photodetectors from these materials with doping levels as high as 10^{15} cm^{-3} owing to the presence of large tunneling currents which are a significant source of detector noise.

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[13]Note that for sample A the depletion region extends to the $In_{0.53}Ga_{0.47}As$/InP interface at the highest voltages. However, the role played by the interface would appear to be minimal since the applied field in this region is much less than E_m. Thus it is unlikely that the same value of θ would be obtained for both samples A and B, where the depletion region in the latter sample is never nearer than 5 μm to the interface at even the highest voltages. See, for example, A. G. Milnes and D. L. Feucht, *Heterojunctions and Metal-Semiconductor Junctions* (Academic, New York, 1972).

Diffusion length determination in *p-n* junction diodes and solar cells

N. D. Arora,[a] S. G. Chamberlain, and D. J. Roulston
Department of Electrical Engineering, University of Waterloo, Waterloo, Ontario, Canada N2L 3G1

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An experimental technique for determining the minority carrier diffusion length in the base region of Si *p-n* junction diodes and solar cells is described. The procedure is to operate the device in the photoconductive mode and to measure its photoresponse in the wavelength region near the energy gap. The ratio of incident light intensity to photocurrent is a linear function of reciprocal absorption coefficient for each wavelength; the slope of the set of points directly yields the diffusion length. In addition, a nonlinear least-squares analysis is also used to determine the diffusion length.

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Minority carrier diffusion length of the base (or substrate) is one of the most important parameters which influence the performance of *p-n* junction diodes and solar cells. Various methods[1-5] exist in the literature for determining the minority carrier diffusion length based on optical and electrical techniques; these involve various tradeoffs between accuracy and convenience. For solar cells and photodiodes it is appropriate to determine the diffusion length L using an optical method. In this letter we describe an experimental technique which uses the photoresponse of the device in the wavelength region 0.9–1.0 μm to determine L. We also obtain the value of L using a nonlinear least-squares fit of the experimental photoresponse to that of the theoretical one, taking L and S, the surface recombination velocity at the contact side, as parameters. Our method is simple and easy to use provided the necessary equipment and computer program are available. As a test the value of L was also calculated using the forward and reverse current method[6]; it was found that L thus obtained has a value much less than that obtained with the present optical method. The reasons are discussed by Neugroschel *et al.*[1]

Consider an n^+-type diffused layer d thick on a p-type base l thick and separated by a space-charge region w thick. When a shallow-junction n^+-p diode is illuminated by a monochromatic radiation of low absorption coefficient such as in the wavelength region 0.9–1.0 μm for silicon, the experimentally measured current is essentially the photocurrent due to carriers collected from the neutral p region. The one-dimensional diffusion equation for the minority electrons n_p in the neutral p region is

$$D_n \frac{d^2 n_p}{dx^2} - \frac{n_p - n_{p0}}{\tau_n} = F_0 \alpha (1 - R) e^{-\alpha x}. \tag{1}$$

Here D_n is the diffusion coefficient, τ_n is the lifetime of the electrons, n_{p0} is the equilibrium concentration of the electrons in the p region, F_0 is the incident photon flux at the surface ($x = 0$), α is the absorption coefficient of incident light, and R is the reflectance of light from the surface. Equation (1) is solved with the following boundary conditions at the depletion layer and metal–p-region boundaries, respectively:

$$n_p(x)\big|_{x=d+w} = n_{p0} e^{qV/kT},$$

$$S_n [n_p(x) - n_{p0}] = -D_n \frac{dn_p}{dx}\bigg|_{x=l+d+w},$$

where S_n is the surface recombination velocity of electrons at the contact side of the p region and V is the externally applied bias of the diode. Solution of (1) with the above boundary conditions and substitution in the current density equation

$$J_n = qD_n \frac{dn_p}{dx}\bigg|_{x=d+w}$$

gives the following expression for the electron component of the photocurrent density in the neutral p region[7]:

$$J_n = \frac{qF_0(1-R)\alpha L_n e^{-\alpha(d+w)}}{\alpha^2 L_n^2 - 1} \left(\alpha L_n - \frac{S_n(\cosh l/L_n - e^{-\alpha l}) + (D_n/L_n)(\sinh l/L_n + \alpha L_n e^{-\alpha l})}{S_n \sinh l/L_n + (D_n/L_n)\cosh l/L_n} \right), \tag{2}$$

[a]On leave from Solid State Physics Laboratory, Lucknow Rd., Delhi 11007, India.

