Electrical Properties of Gold-Doped Diffused Silicon Computer Diodes

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(Manuscript received August 17, 1959)

Planar diffused silicon junctions with storage times of one millimicrosecond or less are readily obtained by gold doping. The introduction of uniform gold concentrations (in the range from 1.2 $\times$ 10^{15} cm^{-3} to 8 $\times$ 10^{16} cm^{-3}) is conveniently done using solid state diffusion techniques. The gold diffusion technique allows relatively precise control of recombination center density, and, although applicable to almost any diffused silicon device, is particularly useful in control of storage time in small-area diffused silicon computer diodes. In this application, reverse recovery time of about one millimicrosecond may be obtained without substantial degradation of other electrical parameters. The process of gold doping by diffusion and its effect on electrical characteristics of diffused silicon computer diodes are discussed. Included are comparisons of first-order calculations and experimental results for variations of reverse recovery time, reverse current and forward current with gold atom density.

I. INTRODUCTION

In transistor circuits designed for high-speed switching or computing operations, computer diodes may perform useful functions. Often the use of computer diodes for such functions as pulse gating or shaping can lead to simplification of logic design, reduction of the number of transistors required and relaxation of circuit tolerances. With high-speed transistor circuitry, these benefits are most readily obtained when the switching times for the computer diodes are comparable to or less than those of the associated transistors. Diffused silicon transistors with good switching characteristics and switching times on the order of 20 millimicroseconds are available.[1] Accordingly, in logic or switching circuits using fast silicon transistors, computer diodes can be used most advantageously if their switching times can be reduced to the low millimicroseconds.

Where the use of silicon transistors is contemplated, comparable leakage currents, temperature characteristics and dc voltage drops strongly suggest the use of silicon junction diodes in associated circuitry. The major problem in design of a suitable silicon junction computer diode is meeting the requirement on switching time mentioned above. If the capacity of the diode is made sufficiently small by the use of a lightly graded junction and a small junction area,[2] the lower limit on the transient response is set by the storage time, or the time required to sweep out excess minority carriers from the region near the junction.

Planar diffused silicon junctions with storage times of one millimicrosecond or less can be readily obtained by doping the silicon with a sufficiently large concentration of recombination centers. This can be done most conveniently after the fabrication of a diffused silicon junction with otherwise suitable electrical characteristics. The solid-state diffusion of gold atoms into the silicon lattice provides a relatively simple and precise means of introducing recombination centers in densities as large as 8×10^{16} cm^{-3} in a prediffused silicon slice. Mesa diodes fabricated with this process (a convenient one for high-level production) can have storage times lower than one millimicrosecond.

In this paper, the process of gold doping by diffusion and its effect on the electrical characteristics of diffused silicon diodes are discussed. Emphasis is on those characteristics pertinent to computer diode applications. Relations between gold atom concentration and reverse recovery time, reverse current and forward current have been obtained experimentally. The reverse current and the forward current at small bias voltages increase directly with the gold atom density. At larger bias voltages, the forward current increases with the square root of the gold atom density. These relations and the approximate magnitudes of the currents can be obtained from first-order calculations that take into account diffusion currents[3] and the recombination and generation of carriers in the p-n transition region.[4] Theory and experiment indicate that the performance of a small-area diffused computer diode is not substantially degraded by gold doping to a level sufficient to decrease the recovery time to one millimicrosecond.

A brief discussion of the desirable electrical characteristics for computer diodes is given in the following section. In Section III the gold diffusion process and the diode structure used in the experiments are described. In Section IV the experimental results are quoted and compared with calculations.

II. ELECTRICAL CHARACTERISTICS OF COMPUTER DIODES

Desirable electrical properties have been briefly mentioned in the introduction. The relative importance of these can be best evaluated by considering the equivalent circuit of Fig. 1, which is a reasonably good representation of a computer diode.[5]

The capacitance C_T is the depletion layer capacitance associated with the space-charge region of the junction. The resistance R_S is an ohmic series resistance dependent on the body resistivities and the diode geometry, including contacts. The remaining p-n junction symbol represents the action of an idealized p-n junction structure, in which diffusive, drift and generative current components may be important. Such a breakdown of the junction diode essentially follows the classical p-n junction treatment of Shockley.[3]

Since these elements, in effect, are all determined by the physical parameters of the diode, they are interdependent to some extent. It is therefore necessary to consider a physical configuration that produces an electrically favorable combination of the above elements. We will not attempt this optimization, but instead consider only the case of a planar diffused junction.

The value of R_S is influenced by body resistivity, the impurity gradient attained by diffusion and the diode geometry. Acceptable values of R_S can be achieved by suitable choice of body resistivity and geometry without introducing other undesirable compromises. The value of C_T is proportional to the junction area and, to a first approximation, varies directly with the cube root of the impurity gradient near the junction. In general, low values of C_T can be achieved by restriction of the junction area and use of a suitably small impurity gradient.[2] The lower limit on the area variation is largely determined by the maximum value permitted for R_S. Further restriction on the impurity gradient may be imposed by specific breakdown voltage requirements.

Assuming that the values of R_S and C_T have been reduced sufficiently, the circuit operation of the device is primarily dictated by the properties of the idealized junction diode element. The important properties of this element are its current–voltage characteristic and its transient response.

We will not consider here the problem of designing a diode with an optimum combination of R_S, C_T and junction element characteristics; instead, optimization of the junction element itself will be discussed. Such individual attention is possible because large variations in forward

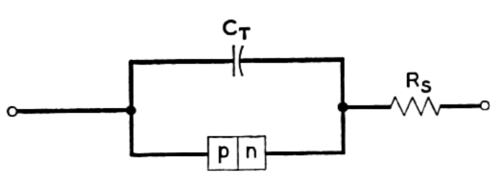

Fig. 1 — Equivalent circuit for a junction diode.

and reverse characteristics and, in transient response, can be obtained almost independently of R_S and C_T by variations in body lifetime.

We will discuss (in Section IV) the transient response, reverse current and forward current as functions of body lifetime, where the lifetime is varied by the addition of known densities of recombinations centers.

III. EXPERIMENTAL DIFFUSED JUNCTION DIODE

3.1 *Junction Diode Structure*

The same basic diode structure (illustrated in Fig. 2) was used in all experiments. The p-n junction is obtained by diffusing boron from high surface concentration into n-type silicon (0.12 to 0.15 ohm-cm). The impurity gradient at the junction is about 10^{21} cm^{-4}. Ohmic contact can

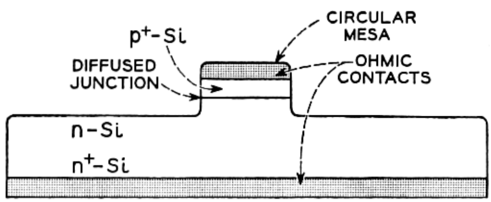

Fig. 2 — Test diode structure.

be made to the highly doped p-type (p^+) silicon near the surface with a suitable gold plating technique. An n^+ layer provided by a phosphorous diffusion allows similar ohmic contact to the n-type silicon.

To permit measurement of body lifetimes in the millimicrosecond range by the reverse recovery measurement technique,[6] a small transition region capacity is required. The junction area is the cross-sectional area of the circular mesa illustrated in the figure. For a mesa of 0.005 inch, values of $C_T < 3\mu\mu$f are obtained. The value of R_S for this geometry is about 12 ohms.

3.2 *Control of Recombination Center Density with Gold Diffusion*

The transient response of a planar diffused diode (to be discussed in more detail in the following section) is determined largely by the carrier lifetimes at the edges of the transition region and in the regions near it. The carrier lifetimes are, in turn, related to the density and nature of the recombination centers in these regions. In our experiments, the recombination centers of interest are provided by gold atoms in the silicon lattice.[7,8] Struthers[9] has measured the diffusion constant and the solid solubility of gold in silicon for the temperature range from 800° to 1250°C. The solubility of gold in silicon has been measured by Collins et al.[7] for the temperature range from 1000°C to 1380°C. Their values do not agree with those reported by Struthers. Later measurements[10] indicate a slightly steeper variation of the solid solubility with temperature than that given in Ref. 9, and values at higher temperatures closer to those reported in Ref. 7. The values of the diffusion constant given in Ref. 9 and the available solubility data indicate that solid state diffusion of gold in silicon should be a reproducible way of introducing gold atoms in silicon to density values at least as large as 8×10^{16} cm^{-3}.

The diffusion constant of gold is substantially larger than that of boron or phosphorus at temperatures up to 1300°C. Thus, it is possible to diffuse boron and phosphorus into a silicon slice, then plate the slice with a thin gold layer and diffuse in the gold without producing substantial changes in the boron and phosphorus distributions. If sufficient time is allowed for the gold diffusion, the concentration of gold in the slice can approach the solid solubility limit corresponding to the diffusion temperature, and the density of recombination centers is determined by the temperature chosen for the gold diffusion. Test diodes similar to the one illustrated in Fig. 2 can then be fabricated from the diffused silicon slice.

IV. EXPERIMENTAL RESULTS

4.1 *Transient Response*

4.1.1 *Reverse Recovery Time Measurement*

For switching applications, the transient response of a diode may be specified in terms of a forward and a reverse recovery time. The forward recovery time is usually substantially shorter than the reverse, and will therefore not be considered. The reverse recovery time is primarily dependent on the body lifetime, and can therefore vary with the density of recombination centers and their recombination cross section.

To clarify subsequent discussion of these variations, the definition and measurement of reverse recovery time will be briefly considered. We have measured reverse recovery time, t_r, under the following conditions: the diode is initially biased to a forward current I_f. A reverse pulse is applied, and the circuit is such that the diode initially conducts a current I_{r0} (equal in magnitude to I_f) in the reverse direction (see Fig. 3). The time dependence of the reverse current is then observed on a travelingwave oscilloscope. This method of test is essentially that discussed by Kingston.[6]

As shown in Fig. 3, the reverse diode current remains constant for a time t_I, while the rate of removal of carriers is determined primarily by the external circuit. When the number of carriers near the junction begins to decrease substantially, the current begins to decrease, approaching the steady-state reverse current for the diode. The time t_{II} is the additional time required for the current to reach a value arbitrarily specified as $0.1I_{r0}$. We will define t_r, the reverse recovery time, to be the sum $t_I + t_{II}$. According to Kingston's analysis (for a simple planar

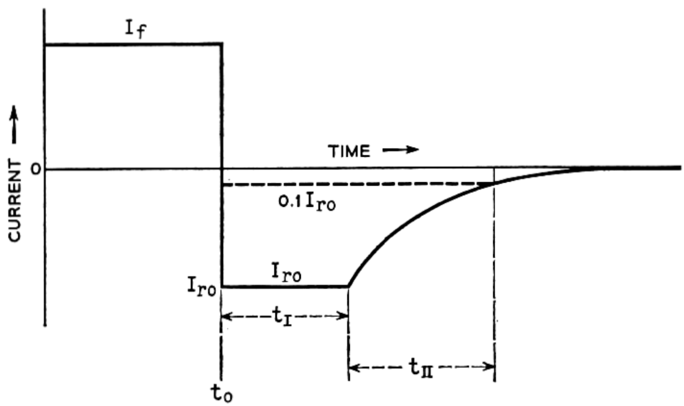

Fig. 3 — Diode reverse recovery pulse.

step-junction) the sum $t_r = t_I + t_{II} \cong 0.9\tau$, where τ is the body lifetime.

Our measurements have been made on diffused junctions. In this case, taking into account the retarding field resulting from the impurity gradient, a similar analysis indicates that t_I is about 0.4τ and t_{II} is about 0.1τ. Thus, we have the sum $t_r \cong 0.5\tau$.

4.1.2 *Dependence of Reverse Recovery Time on Gold Concentration*

The dependence of body lifetime on recombination center density has been considered by Hall,[11] and in detail by Shockley and Read.[12] Only the steady-state value of carrier lifetime will be used in interpretation of recovery time measurements. For a single kind of recombination center, present in density N, with capture cross sections σ_{p0} and σ_{n0} for holes and electrons, at low level of minority carrier injection, the lifetime[12] is given by

$$\tau = \frac{n_0 + n_1}{n_0 + p_0} \tau_{p0} + \frac{p_0 + p_1}{n_0 + p_0} \tau_{n0}, \tag{1}$$

where n_0 and p_0 are equilibrium electron and hole densities,

$$n_1 = n_i e^{(E_t - E_i)/kT},$$

$$p_1 = n_i e^{(E_i - E_t)/kT},$$

($E_t - E_i$ = the difference between the energy level of the trap and the intrinsic Fermi level position) and

$$\tau_{p0} = \frac{1}{\sigma_{p0} v_p N}, \tag{2}$$

$$\tau_{n0} = \frac{1}{\sigma_{n0} v_n N}, \tag{3}$$

where v_n and v_p are thermal velocities for electrons and holes.

We will be concerned with the recombination centers that result from the introduction of gold atoms into the silicon lattice. According to Bemski,[8] recombination in gold-doped silicon is facilitated by two trapping levels associated with each gold atom. These are presumably the acceptor level, E_{t1}, located about 0.54 ev below the conduction band, and the donor level, E_{t2}, about 0.35 ev above the valence band (see Fig. 4)

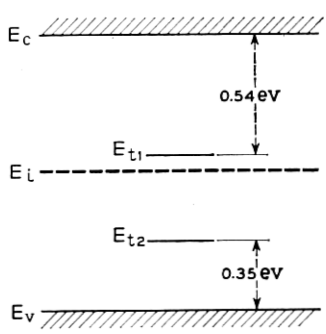

Fig. 4 — Energy levels for gold in silicon.

reported by Collins et al.[7] In n-type silicon, only one of these (E_{t1}) is effective, and in p-type silicon only the other (E_{t2}) is effective[8] (provided the silicon is sufficiently extrinsic). Thus the form of (1) is preserved, whether n- or p-type silicon is considered. However, in n-type silicon, n_1, p_1, τ_{n0} and τ_{p0} refer to the level E_{t1} and, in p-type silicon, these quantities are associated with the level E_{t2}.

In sufficiently extrinsic n-type silicon, the lifetime τ_1 given by (1) reduces to

$$\tau_1 \cong \tau_{p01} = \frac{1}{\sigma_{p01} v_p N}, \tag{4}$$

where τ_{p01} and σ_{p01} are associated with the level E_{t1}. In sufficiently extrinsic p-type silicon, the lifetime τ_2 is given by

$$\tau_2 \cong \tau_{n02} = \frac{1}{\sigma_{n02} v_n N}, \tag{5}$$

where τ_{n02} and σ_{n02} are associated with the level E_{t2}.

It would now appear possible to relate t_r (as measured on a p^+-n diode) and the trap density N, provided σ_{p01} is known, since, as mentioned in Section 4.1.1, $t_r \cong 0.9\tau_1$. In a similar way, with an n^+-p junction $t_r \cong 0.9\tau_2$, t_r can be related to N provided σ_{n02} is known. However, the diffused junctions described in Section 3.1 are more like linearly graded junctions in which minority carrier injection on both sides of the junction must be taken into account. While it is possible to carry out a solution for such a case, it seems intuitively evident that t_r must lie between $\tau_1/2$ and $\tau_2/2$. In this instance, $\sigma_{p01} v_p = 1.38 \times 10^{-8}$ cm^3-sec^{-1} and $\sigma_{n02} v_n = 3.5 \times 10^{-8}$, as given by Bemski.[8] Therefore, to a fair approximation,

$$t_r \cong \frac{2.53 \times 10^7}{N} \tag{6}$$

since τ_1 and τ_2 are almost equal.

Several groups of experimental diodes were fabricated as described in Section III. The density of recombination centers was varied from group to group by varying the gold diffusion temperature in the range from 800° to 1200°C. The recovery time was then measured as a function of the gold diffusion temperature. The results of the experiment are illustrated in Fig. 5. Each circle represents the average t_r for a group of diodes gold diffused at a temperature T_D represented by the corresponding abscissa. The solid bars indicate the range from maximum to minimum t_r as measured for each group, and the dotted bars indicate the estimated precision of the measurement. The number of diodes in each group varies, the largest group (200 diodes) being gold diffused at 1100°C, and the other groups including from five to ten diodes. The dotted line represents the calculated value of t_r using (6) and the values of N taken from available solubility data.[7,10]

Accuracy in measuring the lowest values of t_r is poor. However, it

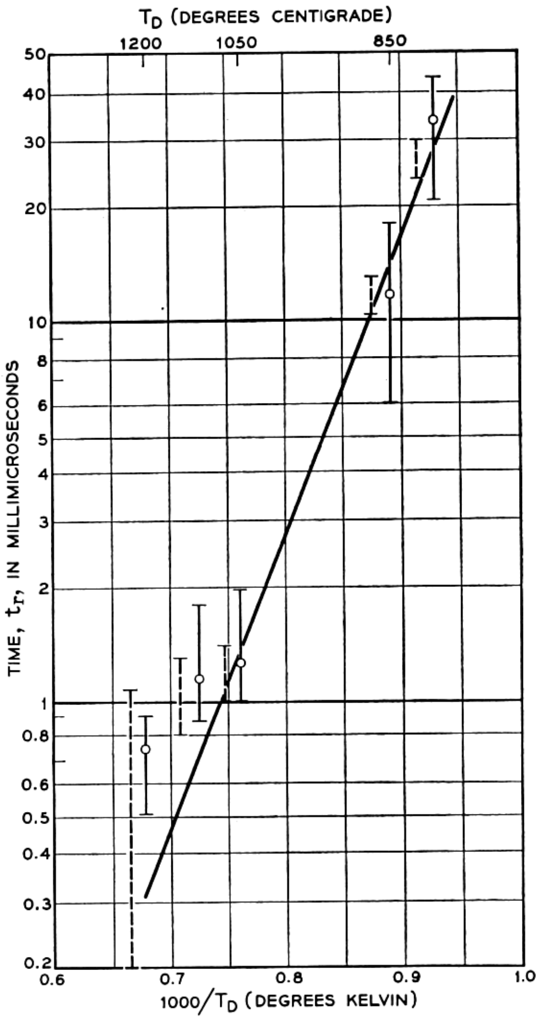

Fig. 5 — Reverse recovery time as a function of inverse gold diffusion temperature.

appears that t_r is inversely proportional to the recombination center density. The better-than-order-of-magnitude agreement between the experimental and calculated values of t_r indicates that the relation between the density of gold atoms and lifetime reported by Bemski[8] can probably be extended to gold concentrations as large as 8×10^{16} cm^{-3}.

4.2 *Reverse Current*

4.2.1 *Reverse Current Arising from Generation in the Space-Charge Region*

There is good experimental evidence that the reverse current in silicon p-n junctions largely arises from carrier generation in the space-charge region.[4,13] According to Shockley and Read,[12] the carrier generation rate, U, is given by

$$U = -\frac{np - n_i^2}{(n + n_1)\tau_{p0} + (p + p_1)\tau_{n0}}. \tag{7}$$

In the space-charge region, for the case of intermediately large reverse bias, it is assumed that $n \rightarrow 0$ and $p \rightarrow 0$, and therefore U_1 reduces to

$$U = \frac{n_i^2}{n_1\tau_{p0} + p_1\tau_{n0}} \tag{8}$$

and the magnitude of reverse current, I_r, is given by

$$I_r = qUWA, \tag{9}$$

where q is the electronic charge, W is the width of the space-charge region, and A is the junction area.

Equation (8) applies to the case of a single-energy level associated with the recombination centers in the swept-out region. For the case of gold-doped silicon, we must consider the recombination levels represented by E_{t1} and E_{t2}. The calculation of the generation rate in the space-charge region, taking into account the respective population of states associated with each gold atom, will not be attempted here. However, an upper limit for the current generated may be obtained. In Fig. 6, at the edge of the space-charge region on the p-type side, the number of effective recombination centers N_{t2} is close to N, and the energy associated with these centers is E_{t2} (substantially less than E_i). Similarly, at the edge of the space-charge region on the n-type side, the number of recombination centers N_{t1} is close to N, and the associated energy level is E_{t1} (close to E_i). Thus, the generation rates, U_1 and U_2, at these edges of the space-charge region are given by

$$U_1 \cong \frac{n_i N}{\dfrac{1}{\sigma_{p01} v_p} + \dfrac{1}{\sigma_{n01} v_n}} \tag{10}$$

and

$$U_2 \cong \frac{n_i N \dfrac{n_i}{p_i}}{\dfrac{1}{\sigma_{n02} v_n} + \left(\dfrac{1}{\sigma_{p02} v_p}\right)\left(\dfrac{n_1}{p_1}\right)^2}. \tag{11}$$

Bemski[8] indicates that $\sigma_{p01} v_p$ differs from $\sigma_{n01} v_n$ only by a factor of two. Thus $\sigma_{p01} v_p$, $\sigma_{n01} v_n$ and $\sigma_{n02} v_n$ are of similar magnitudes. Further, $\sigma_{p02} v_p$ is not substantially less than $\sigma_{n02} v_n$. Then, since $p_1 \gg n_i$, inspection of (10) and (11) indicates that $U_1 \gg U_2$. We will therefore compute the maximum reverse current using the expression

$$I_r = qU_1 WA = q \frac{n_i NWA}{\dfrac{1}{\sigma_{p01} v_p} + \dfrac{1}{\sigma_{n01} v_n}} \tag{12}$$

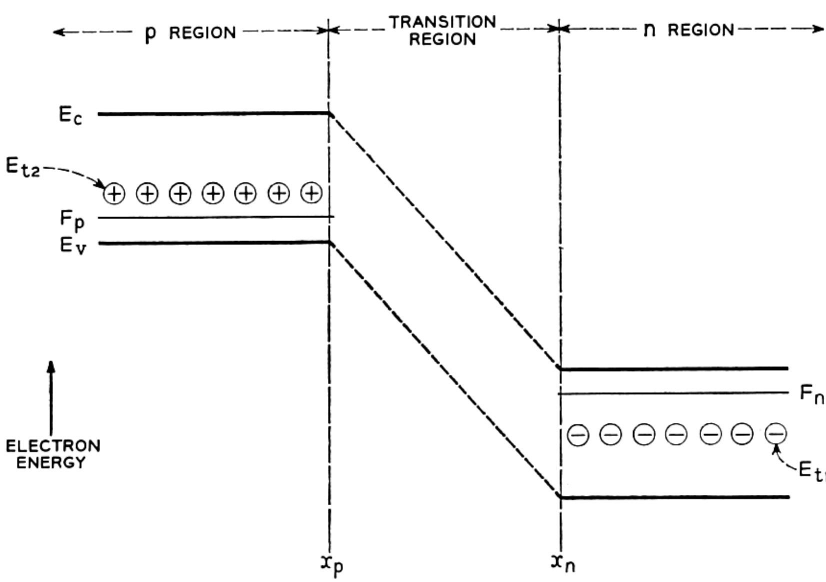

Fig. 6. — Effective recombination centers near the edges (x_n and x_p) of the transition region of a reverse-biased p-n junction; F_p and F_n are quasi-Fermi levels for holes and electrons.

for comparison with our experimental results. For this computation, W has a value of one-half the total space-charge width.

4.2.2. *Reverse Current as a Function of Gold Concentration*

Experimental data for a series of gold-doped diodes is indicated in Fig. 7. The bars represent maximum and minimum values of I_r (measured at a bias voltage of 10 volts) for groups of diodes fabricated from silicon with gold diffused at a temperature indicated on the abscissa. The value of I_r at 10 volts (well below body breakdown voltage) is chosen to minimize error from surface-dependent reverse current components, which often tend to increase with bias more rapidly than does body current. The dotted line is the reverse current calculated from (12), using the cross sections determined by Bemski[8] and the solubility data of Struthers.[10]

The magnitude of the observed reverse current is evidently proportional to N. The agreement between observed and computed values of current is good in view of the very approximate nature of (12).

It is significant from the viewpoint of device design that, for values of gold concentration approaching 8×10^{16} cm^{-3}, recovery time can be less than one millimicrosecond, although the reverse current is still substantially less than 5×10^{-8} ampere.

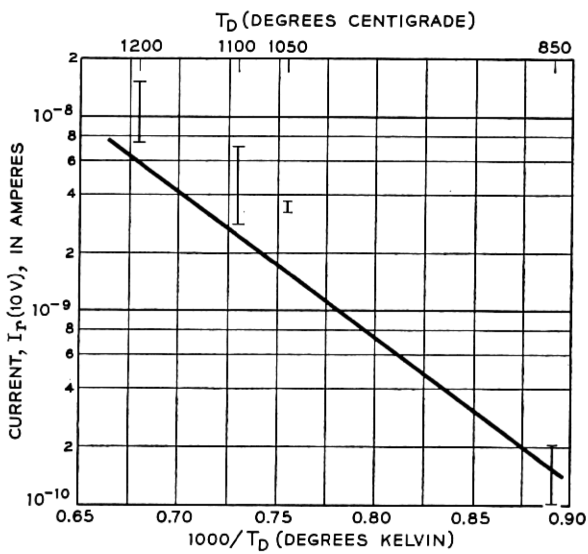

Fig. 7 — Reverse current as a function of inverse gold diffusion temperature.

According to (12), the magnitude of I_r should increase proportionally with W, and therefore for larger values of V vary as $V^{\frac{1}{3}}$, up to biases near breakdown. We have, in general, failed to find this voltage dependence of I_r at voltages greater than 15 volts, although body breakdown voltage for these diodes is between 50 and 60 volts. Both adverse surface conditions and flaws in the silicon body can introduce excess currents that are voltage-dependent, and this discrepancy at higher voltage may result in poor control of these variables. The reason for this discrepancy has not been definitely established; from the practical standpoint, however, the reverse currents are not strong functions of voltage, and are usually less than 0.1 microampere at two-thirds of breakdown voltage for a one-millimicrosecond diode.

4.3 *Forward Current*

4.3.1 *Nature of the Forward Characteristic*

Forward current flow in silicon p-n junctions can arise from diffusion of minority carriers in a region just outside the depletion layer and from carrier recombination in the depletion layer. It has been shown by Sah et al.[4] that the latter mechanism dominates at low current densities and the former dominates at higher current densities. The cross-over from one dominant mechanism to the other occurs in a region of current density that is determined by the nature and concentration of the recombination centers and by the conductivities in the vicinity of the junction. On the basis of analysis similar to that of Shockley[3] for a planar diffused junction, the diffusion current density, J_D, is given by

$$J_D = q\left[\sqrt{\frac{D_p}{\tau_p}}\, p_n(x_n)\cdot\theta_p + \sqrt{\frac{D_n}{\tau_n}}\, n_p(x_p)\cdot\theta_n\right](e^{\beta v} - 1), \qquad (12)$$

where D_p and D_n are diffusion constants for holes and electrons, τ_p and τ_n are hole and electron lifetimes in the n and p regions near the junction, p_n and n_p are equilibrium hole and electron concentrations at the depletion layer boundaries x_n and x_p, and V is the applied voltage.

In the linear grade approximation to the impurity distribution in a diffused junction, θ_p and θ_n are given by[14]

$$\theta_p = \frac{iH_0\left(i\dfrac{x_n}{\sqrt{D_p\tau_p}}\right)}{H_1\left(i\dfrac{x_n}{\sqrt{D_p\tau_p}}\right)} \qquad (13)$$

and

$$\theta_n = \frac{iH_0\left(i\frac{x_p}{\sqrt{D_n\tau_n}}\right)}{H_1\left(i\left(\frac{x_p}{\sqrt{D_n\tau_n}}\right)\right)}, \tag{14}$$

where $i^2 = -1$ and H_0 and H_1 are Hankel functions of the first kind.* For the case of gold-doped silicon, as indicated in Section 4.1.2 [(4) and (5)], $\tau_p \cong \tau_1$ varies with $1/N$, and $\tau_n \cong \tau_2$ varies with $1/N$. Since θ_p and θ_n are slowly varying functions of τ_p and τ_n,

$$J_D \propto \sqrt{N}. \tag{15}$$

The space-charge recombination current[4] is given by

$$J_R \cong \frac{qn_iW}{\sqrt{\tau_{p0}\tau_{n0}}}\frac{e^{\beta V/2}}{\beta(\psi_0 - V)} f(b), \tag{16}$$

where

$$b = e^{-\beta V/2} \cosh\left[\frac{E_t - E_i}{kT} + \tfrac{1}{2}\ln\left(\frac{\tau_{p0}}{\tau_{n0}}\right)\right] \tag{17}$$

and $f(b)$ is as given by Sah et al.[4] Thus:

$$\text{for } E_t \cong E_i \qquad \text{and} \quad \frac{\tau_{p0}}{\tau_{n0}} \cong 1, \qquad f(b) \cong 1;$$

$$\text{for } \left|\frac{E_t - E_i}{kT}\right| \gg 1 \quad \text{and} \quad \frac{\tau_{p0}}{\tau_{n0}} \cong 1, \qquad f(b) \ll 1.$$

In the structure under consideration, recombination current arises from the presence of the two levels, E_{t1} and E_{t2}. Since exact analysis of this situation can be quite complicated, we will assume that the level E_{t1} dominates and calculate J_R from (16), ignoring the contribution from E_{t2}. To some extent this is justified, since $E_{t1} \cong E_i$, $\tau_{p01}/\tau_{n01} \cong \frac{1}{2}$, $(E_{t2} - E_i)/kT$ is about -9.6, and τ_{p02}/τ_{n02} is probably not substantially different from unity. We will therefore assume that J_R is approximately the current that would arise from recombination in that part of the space-charge region between $x = 0$ (at the junction), and x_n. Thus, we have assumed that the level E_{t1} is effective on the n side of the junction. In this case

* Strictly speaking, this analysis is inapplicable, since the assumption made that minority carrier injection does not appreciably alter the "built-in" field at the junction is not strictly valid for forward currents of interest. Consideration of higher injection level not only leads to modification of the field at the junction but also modifies the calculated value of β. However, in cases of interest here the functional dependence of current on doping level will be similar to that of (12).

$$J_R \cong \frac{qn_ix_n}{\sqrt{\tau_{p01}\tau_{n01}}} \frac{e^{\beta V/2}}{\beta(\psi_0 - V)}, \tag{18}$$

and therefore

$$J_R \propto \frac{1}{\sqrt{\tau_{p01}\tau_{n01}}} \propto N. \tag{19}$$

4.3.2 *Forward Current as a Function of Gold Concentration*

Shown in Fig. 8 is a plot of the forward current, I_f, as a function of bias voltage for a typical diode gold-diffused at 1100°C. At low voltages,

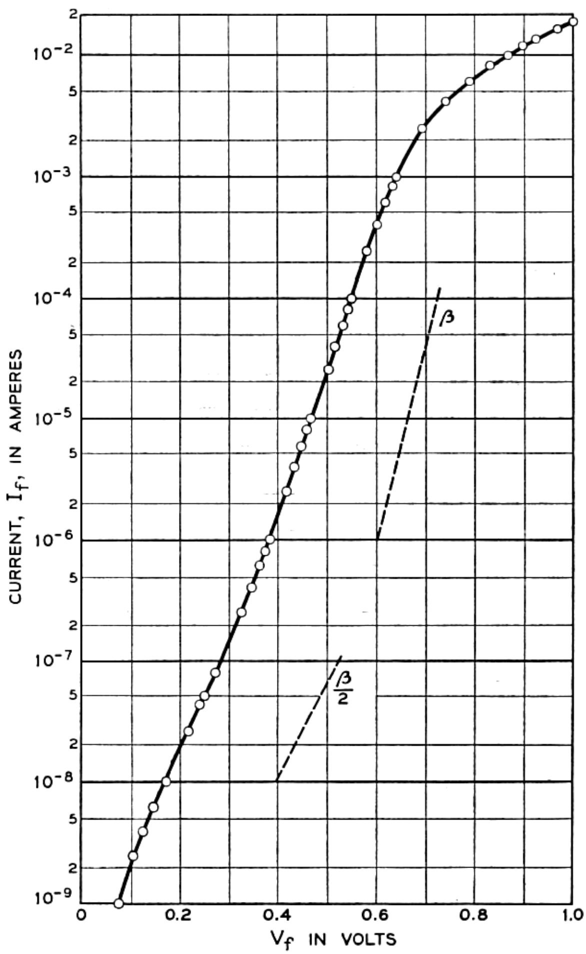

Fig. 8 — Forward current for a typical diode gold diffused at 1100°C.

the slope is close to $\beta/2$ [in agreement with (17)]; at higher voltages, the slope approaches β [in agreement with (12)] and, at still higher voltages, a leveling-off occurs, presumably resulting from series resistance effects. As the gold diffusion temperature is increased, the transition to higher values of β occurs at progressively higher values of voltage, and the magnitude of the current at a given voltage increases.

The effect of gold doping on the forward characteristic has been observed by studying the variation in foward current, $I_f(V)$, with gold diffusion temperature. The recombination current variation is studied by measuring $I_f(0.3)$, where it is expected that (19) should apply. The diffusion current variation is studied by measuring $I_f(0.7)$, where (15) should apply. To obtain the proper value of $I_f(0.7)$, a series resistance

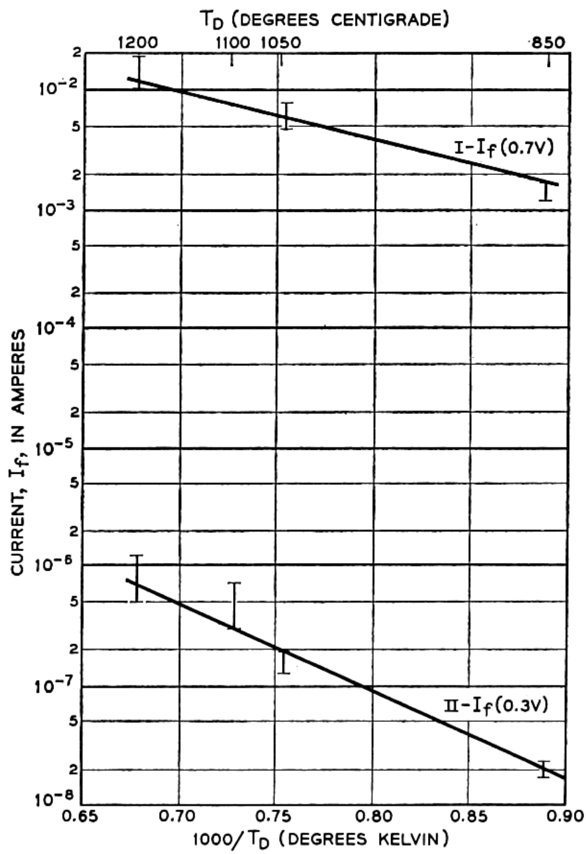

Fig. 9 — Forward current as a function of inverse gold diffusion temperature.

correction must be made. The results of such an experiment are indicated in Fig. 9.

In Fig. 9 (on the upper curve, I), the bars represent the maximum and minimum values of log $I_f(0.7)$ as measured for groups of diodes gold diffused at three different temperatures. These ranges are plotted against $1/T_D$, where T_D is the gold diffusion temperature. According to (15), log I_f is proportional to log $\sqrt{N}$. The solid line in the figure represents the dependence of log $\sqrt{N}$ on $1/T_D$, obtained from Struthers' data.[10] Reasonable agreement is indicated. The magnitudes of the currents calculated from (12) are reasonably close to experimental values, in view of the limited accuracy involved in the use of this equation.

On the lower curve, II, in Fig. 9, the bars represent the ranges of log $I_f(0.3)$, as measured for groups of diodes gold-diffused at various temperatures. According to (19), log $I_f(0.3)$ should vary linearly with $1/T_D$ in the same manner that log N varies with $1/T_D$. The solid line in the figure indicates the dependence of log N on $1/T_D$ from the solubility data. Again, the agreement is reasonably good. However, the magnitude of the currents calculated from (18) are, for this case, sizably less than the indicated experimental values, the discrepancy being larger than expected even when the inaccuracies of the calculation are considered.

V. CONCLUSIONS

The reverse recovery time of diffused silicon p-n junctions can be reduced to one millimicrosecond or less by gold doping. The decrease in recovery time results primarily from a decrease in minority carrier lifetimes in the p and n regions at the edges of the transition region.

It is found that, to a first approximation, the reverse recovery time is inversely proportional to the gold atom concentration, if the latter quantity is estimated from the measured solubility[7,10] of gold in silicon. Measured values of the recovery time are in agreement with calculated values using recombination cross sections measured by Bemski.[8]

Relatively simple diffusion techniques permit the introduction of desired gold concentrations within the range 1.2×10^{15} to 8×10^{16} cm^{-3}. If initial carrier lifetimes in the silicon diode are sufficiently high, then a desired recovery time value between 0.7 and 35 millimicroseconds may be reproduced to within ± 60 per cent or better. At higher levels of gold concentration, uncontrolled impurities introduced during diffusion and thermal cycling tend to be swamped out, and recovery time is probably more reproducible. However, accurate measurement of t_r in this range is difficult.

Reduction of recovery time to one millimicrosecond or less is accompanied by changes in the reverse and forward diode characteristics. The reverse current (at lower bias voltages), primarily generated in the space-charge region, increases in proportion to the gold atom density. The forward current in a gold-doped diode has space-charge recombination and diffusion components. The former component increases directly with the gold atom density, and the latter increases with the square root of the gold atom density.

These changes in characteristics are not sufficient to substantially degrade the performance of a diffused diode suitable for computer applications. Reverse current can be kept well below circuit requirements by minimizing the junction area. The relative increase in the space-charge recombination component of the forward current introduces only a small increase in dynamic forward resistance in a rather limited portion of the current voltage characteristic, and can serve to lower the dc drop at low forward bias. Thus, gold doping of a small-area diffused silicon diode can produce a relatively high-performance computer diode with transient response better than one millimicrosecond.

VI. ACKNOWLEDGMENT

The authors wish to acknowledge the help of R. L. Rulison and D. F. Ciccolella in the fabrication of gold-diffused silicon diodes. Acknowledgment is also due W. C. Meyer and Miss F. R. Lutchko for electrical measurements.

REFERENCES

1. Miller, L. E., I.R.E. Wescon Conv. Rec., Vol. 2, Part 3, 1958, p. 132.
2. Forster, J. H. and Zuk, P., I.R.E. Wescon Conv. Rec., Vol. 2, Part 3, 1958, p. 122.
3. Shockley, W., B.S.T.J., **28,** 1949, p. 435.
4. Sah, C. T., Noyce, R. N. and Shockley, W., Proc. I.R.E., **45,** 1957, p. 1228.
5. Uhlir, A., Jr., Proc. I.R.E., **44,** 1956, p. 1184.
6. Kingston, R. H., Proc. I.R.E., **42,** 1954, p. 829.
7. Collins, C. B., Carlson, R. D. and Gallagher, C. J., Phys. Rev., **105,** 1957, p. 1168.
8. Bemski, G., Phys. Rev., **111,** 1958, p. 1515.
9. Struthers, J. D., J. Appl. Phys., **27,** 1956, p. 1560.
10. Struthers, J. D., unpublished results.
11. Hall, R. N., Phys. Rev., **87,** 1952, p. 387.
12. Shockley, W. and Read, W. T., Jr., Phys. Rev., **87,** 1952, p. 835.
13. Veloric, H. S. and Prince, M. B., B.S.T.J., **36,** 1957, p. 975.
14. Bakanowski, A. E., unpublished work.