smaller by a factor of two, the error would be about 20 percent. This source of error can be diminished by making the epitaxial base thinner. If $W_B \simeq 5\ \mu$m, for example, uncertainties of a factor of two in τ_{BF} would introduce only about 5 percent error.

The experimentally determined values of τ_E and Q_E yielded by the method can be used to study the energy-gap shrinkage and recombination mechanisms present in the emitter. The details of this type of study have appeared in [15], which dealt with the closely related problem of studying these mechanisms in solar cells. The study involves comparing the experimentally determined values of τ_E and Q_E with those calculated using various models for emitter recombination and energy-gap shrinkage [1]–[10].

To make a coarse estimate of an average energy-gap shrinkage in the emitter, one can use an expression developed in [15]: $\Delta E_G = kT \ln (Q_{E0}/Q_{E0}^0)$ where $Q_{E0}^0 \simeq (qn_i^2/N_{DD}) W_E/\ln(N_{\text{MAX}}/N_{DD})$ and where N_{DD} is the doping density at the edge of the emitter space-charge region, N_{MAX} is the maximum electron concentration in the emitter, and W_E is the quasi-neutral emitter thickness. If N_{DD} is assumed to be about 10^{15} cm^{-3}, equal to the base doping concentration, the use of this expression gives $\Delta E_G \simeq 77$ mV, as stated in Table I.

For determining τ_E and Q_E of the emitter, a transistor structure has an advantage over the diode structures used in [15] and [16]. For a short-base diode, for example, the calculation of Q_{B0} from $Q_{B0} = (qn_i^2 W_B)/(2kT/q)N_{AA}$ requires that n_i and N_{AA} are accurately known. This necessitates precise temperature control during the experiments; it also involves some uncertainties about N_{AA} as inferred from reverse capacitance–voltage characteristics. For the transistor structure, however, $Q_{B0} = I_{C0}\tau_F$, in which I_{C0} can be measured with great accuracy.

For some transistors, another advantage might exist in that the quasi-neutral capacitance C_{QN} might dominate the total capacitance at high temperatures. Then τ_{QN} could be determined from a single measurement of the open-circuit voltage decay [24], and $\tau_E \simeq \tau_{QN}$ if, in addition, h_{FE} (ideal) is small.

The purpose here has been to outline briefly the method for determining τ_E and Q_E, and to demonstrate it with a single example. We are now applying the method to various commercial transistors, and detailed discussions of its range of applicability and of the results it yields are planned for the future. We are also adapting this method to the study of the physical mechanisms in the emitter that are apparently responsible for limiting the open-circuit voltage seen in low-resistivity silicon solar cells [15].

Acknowledgment

The authors wish to thank the reviewer for very useful comments.

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A Useful Method for Approximating the Profile of Ions Implanted Through a Thin Film

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***Abstract*—An approximate calculation method is presented for finding profiles of ions implanted through a thin film, based on**

Manuscript received June 6, 1977; revised August 3, 1977.
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standard range tables. Both the projected range and straggling in the substrate are calculated.

Ion implantation through a thin film is used quite frequently in semiconductor device fabrication processes. The thin film may serve as surface passivation, to prevent out-diffusion in subsequent process steps, or in order to locate the distribution peak at the interface. In some cases, the implantation is performed through a thin metallic layer, which is later used as a contact to the device. Such films affect the distribution profile in the substrate. Our purpose is to obtain an approximation to the implantation profile in such a case, to be used in design for selection of film thickness, implantation energy, and fluence.

Often an ion implantation process step is planned assuming a Gaussian distribution of implanted atoms in the substrate. The projected range R_P and straggling ΔR_P of the distribution as a function of energy are taken from standard tables [1], [2], calculated from LSS theory, for several combinations of ion and substrate. A natural approach to the implantation-through-a film problem is to convert the film to a substrate-layer of equivalent thickness, and proceed normally with the ion–substrate combination [3]. However, such a conversion cannot account for the fluence, projected range, and straggling of the implanted ions simultaneously.

We take a different approach. Assuming the resulting distribution to be Gaussian let us calculate each of the parameters separately, using the standard tables.

First, the fluence into the substrate is found, noticing that the number of ions stopped in the film is independent of what follows. We find this number using tables for the ion-film combination, with the original energy E_0. We then substract it from the original fluence to find the fluence into the substrate.

Second, the average projected range in the substrate is found in the ion-substrate table, being the range of an ion beam with energy E_1. E_1 is the average energy of the beam entering the substrate after traversing the film, and it is found from the ion-film table as follows:

1) Find the projected range $R_p(E_0,\text{film})$ that the original beam would have in the film material if it was infinitely thick.

2) Substract the mask thickness d.

3) Find E_1 as the energy required for a beam to have a range

$$R_p(E_1,\text{film}) = R_p(E_0,\text{film}) - d. \tag{1}$$

4) If $R_p(E_0,\text{film}) \leqslant d$, the final projected range is $R_p(E_0,\text{film})$ itself, in the film.[1]

Third, we find the straggling in the substrate. Note that this straggling must be larger than the value found in the ion-substrate table for energy E_1, $\Delta R_p(E_1,\text{substrate})$, because E_1 is only the average energy of the beam, which already contains the contribution of the mask to the final straggling. Since the energy of each ion is a random variable affected by many independent collisions, the variance of the energy distribution is the sum of independent contributions. Assuming that the specific energy loss is constant over the energy range of ions entering the substrate, the variance in energy is related to the straggling in range by [4]:

$$\overline{\Delta R_p{}^2} = \left(\frac{d\overline{R_p}}{dE}\right)^2_{E_1} \overline{\Delta E^2}. \tag{2}$$

This assumption is consistent with the initial one that the distribution is Gaussian. Thus the square of the straggling of a beam in the film material must be expressible as a sum of squares:

$$\overline{\Delta R_p{}^2}(E_0,\text{film}) = \overline{\Delta R_p{}^2}(E_1,\text{film}) + \Delta(\overline{\Delta R_p{}^2}) \tag{3}$$

$\Delta(\overline{\Delta R_p{}^2})$ being the contribution of the film of thickness d. The contribution of the film to the variance in energy of the beam entering the substrate may thus be calculated by:

$$\Delta(\overline{\Delta E^2}) = [\overline{\Delta R_p{}^2}(E_0,\text{film}) - \overline{\Delta R_p{}^2}(E_1,\text{film})] \Big/ \left(\frac{d\overline{R_p}}{dE}\right)^2_{E_1,\text{film}}. \tag{4}$$

This energy variance may be reconverted to a component of straggling in the substrate, by multiplying it by $(d\overline{R_p}/dE)^2_{E_1,\text{substrate}}$. Finally, the total straggling in the substrate may be expressed as the rms value of its components:

$$\Delta R_p = \left\{[\overline{\Delta R_p{}^2}(E_0,\text{film}) - \overline{\Delta R_p{}^2}(E_1,\text{film})] \cdot \frac{(d\overline{R_p}/dE)^2_{E_1,\text{substrate}}}{(d\overline{R_p}/dE)^2_{E_1,\text{film}}} + \overline{\Delta R_p{}^2}(E_1,\text{substrate})\right\}^{1/2}. \tag{5}$$

All the quantities in this expression appear in the range table for the ion-film and ion-substrate combinations. The derivatives may be approximated by finite differences.

The simplifying assumptions made here are no worse than the initial and commonly made assumption, that the distribution is Gaussian. The errors thus introduced are of the same order of magnitude as those already present.

The effect of a film on the resultant profile is important especially when its atomic number differs considerably from that of the substrate. This effect is demonstrated by the following numerical example: Implant 10^{14} cm^{-2} of 200 keV B^+ into a silicon substrate through 1000 Å of gold. 2×10^{13} cm^{-2} remain in the gold, the rest arrive at the interface with $E_1 = 104$ keV. The final projected range in the silicon is 3100 Å and the straggling is 2400 Å. On the other hand, if we simply say that 1000 Å of gold are equivalent to 2200 Å of silicon, we arrive at the same projected range but a straggling of only 920 Å.

In the case of an implantation into silicon through silicon dioxide the effect of the film is less important. For example, 200 keV P^+ through 1000 Å of Si, will reach 1325 Å into the substrate, with a straggling of 730 Å. An equivalent layer of 1215 Å of Si would produce a straggling of 775 Å. The numerical values in these examples have been taken from [1].

[1] If the film thickness is larger than $R_p(E_0,\text{film})$ the approximation presented here does not give the straggling in the substrate. Its extension to such cases must include higher moments.

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Nondestructive Determination of the Depth of Planar p-n Junctions by Scanning Electron Microscopy

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***Abstract*—A method was developed for measuring nondestructively the depth of planar p-n junctions in simple devices as well as in integrated-circuit structures with the electron-beam induced**

Manuscript received July 11, 1977. This work was supported by NASA.

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