As a summary, it is found that the introduction of etch flow in our system offers the advantage of in situ etching of chemically unstable phases in the growth of epi layers. However, a low etch flow rate must be used to obtain a low intrinsic defect density. Stringent screening of solid GaAs source material is required to minimize impurity incorporation.

Conclusion

A solid GaAs source, VPE system has been used to grow epi layers suitable for device applications. The electron trap observed in such grown layers is identified as EL2 while the three hole traps detected (H0.24, H0.43, H0.50) are found to be intrinsic defect, copper, and iron related defects, respectively. The concentration of these traps is not higher than those reported for epi wafers grown by liquid Ga method. By examining the effect of growth parameters on hole trap concentration, we concluded the following.

1. Impurity transport from solid GaAs source to the growing epi layer is the major source of impurity-related hole traps detected in our epi wafers.

2. Low etch flow rate is preferred for minimizing both intrinsic defects and impurity-related deep traps in the epi layer. However, minimizing deep traps requires an increase in the growth rate which degrades the active/buffer layer interface sharpness.

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Minority Carrier Diffusion Length Mapping in Silicon Wafers Using a Si-Electrolyte-Contact

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ABSTRACT

A method has been developed to determine the minority carrier diffusion length and its lateral distribution in considerable detail by measuring the back-surface photocurrent (BPC) of a semiconductor. The wafer is illuminated with a laser at the front side and is provided with electrolyte-contacts on both sides.

With ever increasing complexity of IC's, the suitability of the Si wafers used for a particular process is becoming more and more critical. In particular, contamination of the wafers with fast-diffusing metals usually leads to disastrous results. Whereas analytical techniques for the detection of these impurities do exist (e.g., neutron activation analysis), their use in routine wafer quality control is hampered by very low through-put and high costs. Fast and simple methods are needed; presently, however, only the so-called haze-test in conjunction with rapid annealing is suited for the task (1). Haze-tests, however, are limited to metals that form precipitates and are therefore insensitive to the well-known Si-"poisons" as, e.g., Au, Fe, Cr, ... (2). These metals do not easily precipitate but remain in solid solution thus decreasing the minority carrier lifetime or diffusion length.

In principle, these contaminants could be detected by measuring the diffusion length L of the minority carriers in the wafer. The commonly used methods for doing this, e.g., surface photo voltage (SPV) (3), can be used, but SPV and other methods generally suffer from three serious shortcomings if they are utilized for wafer quality control: (i) Inaccuracy for relatively large diffusion length $(>100 \ \mu m)$ (4). (ii) Only a small part of the wafer depth is probed. (iii) Mapping of the total wafer area is practically impossible.

To avoid these disadvantages, a new method is described. In contrast to standard SPV techniques the minority carriers generated by illuminating the front surface of the sample are collected by a space charge region on the back. All carriers contributing to a signal on the front of the specimen have to travel across the specimen. The relation between the number of carriers generated by light at the front and the number collected at the rear contains the information about the diffusion length with the only limitation for large diffusion lengths being the specimen thickness. If a laser beam is used as the light source, laser scanning allows fast mapping of L even for large wafers in a short time.

All earlier efforts to measure the back-side photo current (5, 6) suffer from extended specimen preparation (e.g., diffused p⁺pn⁺ structure, oxide films, etc.). In contrast, the described method is simple because the collecting contact for the minority carriers is formed by a semiconductor electrolyte contact (SEC) on the back; thus no preparation of the wafer is necessary. [Using a SEC and measuring the wavelength dependence of the short-circuit current is also a common variation of the standard SPV technique (7, 8)]. Moreover the SEC can also be employed to reduce the surface-state density on the front (a necessary prerequisite of the method) as will be shown.

Theory

Consider a space charge region (SCR) at the back of the sample (cf. Fig. 1B) and illumination at the front. The diffusion-current density at the depletion edge is a function of the diffusion length L, the parameter of interest in this paper. The generation rate g(x) of electron hole pairs at a distance x from the illuminated surface is given by

$$q(x) = P\alpha \exp\left(-\alpha x\right)$$
 [1]

where P is the total number of photons absorbed by the

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Fig. 1. Schematic cross section of the sample and configuration (A) to measure the front-side current I_o and (B) to measure the back surface diffusion current I_g .

semiconductor per unit area and α the absorption-coefficient for the used wavelength.

The generation, diffusion, and recombination for n-type silicon in steady state is described by

$$D_{\rm p} d^2 p / dx^2 + g(x) - (p - p_{\rm o}) / \tau_{\rm p} = 0$$
 [2]

where D_p is the diffusion-coefficient for holes, p the hole density, p_o the equilibrium-density of holes and τ_p their lifetime. The general solution of this equation is [cf. Ref. (9)]

$$p = A \exp (x/L) + B \exp (-x/L) + (P\alpha L^2)/(D_p(1 - \alpha^2 L^2)) \exp (-\alpha x) + p_\alpha$$
[3]

L is the diffusion length and *W* the SCR width. With the boundary conditions p = 0 at x = D - W (minority carrier concentration is assumed to be zero at the depletion edge) and dp/dx = 0 at x = 0 (no recombination at the illuminated surface, *i.e.*, very low surface state density) and the assumptions $P >> p_0$ (equilibrium-density of holes is negligible compared with the number of photogenerated holes) and D >> W (specimen is much thicker than SRC width) we obtain for the diffusion-current-density J_{diff} (with the elementary charge q)

$$J_{\rm diff} = -q D_{\rm p} \, dp/dx \qquad [4]$$

at the depletion edge x = D - W using Eq. [3]

$$J_{\rm diffB} = 2qP\alpha^2 L^2 / \{\alpha^2 L^2 - 1\}$$

$$(\exp((W - D)/L) + \exp((D - W)/L))$$
 [5]

This equation cannot be solved analytically for L. J_{diffB} is the current density under reverse bias at the back of the sample further on designated as I_g (referenced to 1 cm²) which is the measured quantity.

Now we assume a SCR region at the illuminated front of the sample (cf. Fig. 1A). We obtain the current-density of the carriers generated in this SRC region

$$J_{\rm scr} = qP(\exp\left(-\alpha W\right) - 1)$$
 [6]

For short wavelengths and a large space charge region, all minority carriers are collected and J_{scr} simply equals -qP ($J_{diffA} = 0$), further on designated as I_0 (referenced to 1 cm²). If I_g/I_0 is plotted vs. D - W with L as parameter, the set of curves shown in Fig. 2 results.

In an extended theory the influence of the surface recombination velocity S can be taken into account [cf. Ref. (9)]. If the minority carrier density p is calculated as a func-



Fig. 2. Computed I_g/I_o ratio as a function of the specimen thickness minus the SRC width W with the diffusion length L as parameter (lines). Measured I_g/I_o ratio of three mechanically thinned specimens with different diffusion lengths. Triangles: $L = 63 \mu$ m, p-Si (boron), CZ, 0.1 Ω cm. Circles: $L = 600 \mu$ m, p-Si (boron), CZ, 1 Ω cm. Squares: $L = 2400 \mu$ m, p-Si (boron), FZ, 16.8 Ω cm.

tion of depth with S as parameter, the curve shown in Fig. 3 result. It can be seen that for S < 100 cm/s the measured value of L is essentially correct.

Experimental

Experimental setup.—One of the boundary conditions of the theory requires zero carrier recombination at the illuminated surface. A free-floating specimen surface would not necessarily fulfill this condition whereas a high quality oxide [that can be obtained with a surface recombination velocity of about 20 cm/s (10)] should be sufficient. To determine the effect of surface recombination at the front, the photocurrent I_g of a p-type sample (5 Ω cm, 1-0-0, CZ) covered with a high-quality 20 nm gate-oxide is compared to the photocurrent after the oxide was etched off and the



Fig. 3. Computed minority carrier distribution with the surface recombination velocity S as parameter. (Boundary conditions $I_o = 10$ mA/cm², $L = 500 \mu$ m, wavelength = 950 nm.)



Fig. 4. Diffusion current I_g as a function of the used wavelength and the properties of the illuminated surface.-(Sample: p-Si (boron), CZ, 5 Ω cm, $D = 525 \mu$ m, $L = 140 \mu$ m, 20 nm dry oxide.

surface was in contact with either electrolyte, air, or water. Figure 4 illustrates the results: I_g was measured as a function of the wavelength of the illuminating light first with thermal oxide on the illuminated surface. Then I_g was measured while the oxide was replaced by the electrolyte, by air, and finally by water. The total photon flux for each wavelength was constant, controlled by a Si-photodiode as reference. The results demonstrate that: (i) The surface recombination at a SEC is comparable to that of an oxide interface within the measurement accuracy, while the other surface conditions produce higher surface recombination rates indicated by the lower I_g signal for short wavelength illumination. Actually the surface recombination velocity of Si (and Ge) immersed in a HF solution appears to be the lowest ever reported. For (1-1-1) Si a surface recombination velocity of 0.25 cm/s was reported by Yablonovitch et al. (11). (ii) The diffusion current is independent of the wavelength if it is shorter than 700 nm.

A detailed description of the properties of an electrolytic contact for semiconductors is given in Ref. (12). Briefly, a SEC is roughly comparable to a Schottky contact in its electrical behavior and has the advantages that it allows the production of fresh surfaces by electropolishing and that it is transparent for all wavelengths used.



Fig. 5. Cross-sectional view of the electrolytic double cell and its electrical connections to ammeter and potentiostat.



Fig. 6. Current-potential curves for dark and illuminated p- and n-Si electrodes in a 2.5 w/o HF-electrolyte (scan rate 100 mV/s) vs. Pt counterelectrode.

For our measurements we used a symmetric double cell (Fig. 5) with the sample front and back surface contacted by electrolytes. In addition to this double SEC an ohmic contact to the specimen was provided by a Ga-In-eutectic [24 weight percent (w/o) In]. This arrangement allows one to measure the number of carriers that diffuse through the sample by collecting all these carriers in a SCR on the back (back SEC operated in reverse bias measuring I_g ; front SEC floating) and also the total number of generated carriers and thus the quantity P (number of photons) directly by operating the front SEC in reverse bias obtaining I_0 . In this case J_{diffA} (Fig. 1A) can be neglected for the wavelength employed; this is easily checked experimentally by measuring I_0 as a function of the reverse voltage. If a variation of the applied voltage (or SCR) does not change I_{o} , that all minority carriers generated will be accounted for in I_0 . This procedure not only has the advantage of avoiding the use of a calibrated light detector, but moreover assures that reflection and absorption of light at the cell windows and the specimen surface do not falsify the measurement.

The electrolyte is 2.5 w/o HF with some drops of a wetting agent ("Mirasol," produced by Tetenal).

A tungsten halogen lamp or a HeNe-laser was used for illumination of the specimen front surface. A filter absorbed photons with wavelengths exceeding 800 nm. So all carriers are generated in a small zone at the front.

A Wenking potentiostat POS 73 and a Pt wire as reference electrode were used for the measurements. By switching between terminal 1 or 2 the operating cell (front or rear) could be selected (comp. Fig. 5).

Properties of the SEC for p- and n-Si.—Current flow across the SEC is always accompanied by chemical reactions. For diluted HF electrolytes the possible reactions



Fig. 7. The ratio n collected charge carriers per incident photon as a function of the current density across the SEC for 2.5 w/o HF in aqueous solution. With the region A of constant n and B of linear n.

are H_2 evolution at negative (cathodic) bias and Si dissolution for positive (anodic) bias. Figure 6 shows the simplified I-V-curve for p- and n-type silicon.

For a reversely biased p-type Si contact only H_2 evolution occurs. For this process the ratio *n* of collected charge carriers per generated minority carriers is exactly 1. This means that for p-type Si the details of the electrochemical processes can be neglected: all minority carriers that travel through the wafer are collected and measured as I_g .

For n-Si the reaction is more complex because the photocurrent is measured in the anodic region of the I-Vcurve (compare Fig. 6). Below a critical current density J_{ps1} the chemical dissolution mechanism changes and electrons are injected [for more details compare Ref. (12-14)]. This way the ratio n changes from 1 to higher numbers. For an electrolyte concentration of 2.5 w/o HF, Fig. 7 shows the ratio *n* as a function of the current density *J*. Important for the measurements is the existence of a region with constant *n* for J > 25 mA/cm² and of a region with a linear dependence of n on J for $1 \text{ mA/cm}^2 < J < 15 \text{ mA/cm}^2$. The constant region seems to be most suitable for L measurements but requires unfavorable high current densities for I_o because I_g has to be greater than the lower limit 25 mA/cm². This leaves the linear region with the restriction $I_g/I_o > 0.1$ (this implies $D < 3 \cdot L$; compare Fig. 2). In this range the linearity is acceptable and the I_g/I_o ratio can be corrected by multiplying with $(c - I_o)/(c - I_g)$ (c = 86 mA for an electrolyte concentration of 2.5 w/o HF). It is noteworthy that anodic dissolution (especially for highly doped n-Si) changes the specimen surface to a dark or dim color after some minutes. Since this effect could influence the results, the measurements should be performed as fast as possible.

Measuring instructions.—The following instructions are for p-type samples. Wherever necessary, values for n-type wafers are in brackets. N-type samples must be strongly illuminated while electropolishing. Specimen preparation is fast and simple: (*i*) Chemical polishing of the specimen, CP4 etch for 2 min, if only unpolished surfaces are available. (*ii*) Rubbing with Ga-In eutectic around the edge of the sample to produce an ohmic contact.

The measurement is carried out as follows: (i) Determination of the specimen thickness and mounting in the double cell. (ii) Electropolishing of both sides for 2 min: sample at +10V; producing about 100-300 mA/cm². (iii) Electropolishing of the (illuminated) front surface for 10s; then open circuit. (iv) I_g is measured at the dark back: sample at -(+) 5V vs. back reference electrode while front is illuminated. (v) Total photocurrent I_o is measured by switching from the back to the front cell with same illumination and voltage. (vi) Removal of the sample and deter-



Fig. 8: Dependence of the measured diffusion length L on the total number of absorbed photons specified by the photocurrent I_a (sample: p-Si (boron), FZ, 16.8 Ω cm, D = 2280).

mination of its thickness *D*. In order to avoid possible surface interference it is recommended repeating steps (iii) to (v) until the measured values of the current are stable.

Results and Discussion

The ratio I_g/I_o in relation to the specimen thickness D minus the SCR width W was computed for different diffusion lengths (see Fig. 2). To determine the accuracy of the method, the diffusion lengths of three specimens were measured as a function of their thickness. This means that after a measurement the specimen was mechanically thinned and then measured again. The results of this experiment are shown in Fig. 2. The agreement between the computed curves and the measured points is excellent. Only for $I_g/I_o > 0.8$ (equivalent $D - W < 0.7 \cdot L$) the measured values deviate considerably from the theoretical curves. The measurements were carried out at a photonflux of $6.24 \cdot 10^{16}$ /s · cm² corresponding to a photocurrent of $I_0 = 10 \text{ mA/cm}^2$. The magnitude of the carrier concentration at the illuminated surface then is 1013 cm^{-3} -10¹⁴ cm^{-3} depending on the specimen thickness and diffusion length.

From the literature (15-19) it is known that the diffusion length L (or the lifetime of minority carriers) is a function of the concentration of minority carriers.

Experimentally, this is hard however to investigate for SPV because the light intensities are usually very low because of high absorption of the filters and cannot be varied much (usually less than one order of magnitude). This situ-



Fig. 9. By scratching with a Fe wire (V-pattern) and following rapid optical annealing (1200°C, 30s) a Si wafer [CZ, p-type (boron), 5 Ω cm, $D = 525 \ \mu$ m], was contaminated (A). Then it was mounted in the double cell (area inside the dotted line exposed to the electrolyte) and illuminated by a scanned laser beam while the diffusion current I_g was plotted simultaneously. (B) shows the measured profile.

ation is different for BPC; the photon flux is easily controlled over three orders of magnitude by using different gray filters. The dependence of the diffusion length L on the light intensity, proportional to the minority carrier concentration and expressed by the photocurrent I_{o} , is shown in Fig. 8. Trap saturation with increasing minority carrier density could explain this effect [calculated lifetimes for Si as a function of excess carrier concentration and doping density are given by Meier et al. (19)]. The strength of the method, however, is not to measure absolute values of L (defined for some boundary conditions as, e.g., minority carrier density), but to permit fast evaluation of samples with large diffusion lengths (in relative units), and in its ability to measure lateral variations of the diffusion length with ease. For the latter the specimen is illuminated with a laser beam (630 nm, 10 mW) that is scanned across the surface. Since measurements with one wavelength are sufficient to obtain L and since the photon flux can be made to be constant, I_g yields directly the lateral diffusion length distribution in a sample. This is demonstrated by the result obtained from an intentionally contaminated 4 in.-wafer (Fig. 9A). The back of the wafer was lightly scratched with an Fe wire in a V pattern. After subsequent annealing (1200°C, 30s) and by using a 4 in.-version of the specimen holder shown in Fig. 5 combined with a He-Ne-laser, the I_g distribution shown in Fig. 9B was obtained. The scan time in this case (resolution = 1 mm^2) was 20 min and limited by the mechanical components of the system. The correlation with the intentional contamination is obvious; but unexpected contamination spots (lower left half) were also found. It is remarkable that no precleaning or electropolishing was needed to measure the $I_{\rm g}$ distribution [only step (iv) of measuring instructions was executed]. The "ohmic" contact was provided by four tungsten-carbide needles at the edge of the wafer which, although not really "ohmic," is sufficient for the small currents ($I_o < 1.5$ mA) involved.

If the laser beam is focused, the minority carriers diffuse in a conical distribution to the back surface, consequently the maximal lateral resolution of the method is approximately equal to the specimen thickness.

The laser scanning BPC method is complementary to the Haze-method (2) because it preferentially detects "lifetime-killers" that do not easily precipitate while the Hazemethod only detects contaminants which are precipitated and therefore exert a smaller influence on the lifetime.

Conclusions

The measurement of the back surface photocurrent in an electrochemical double cell gives fast and detailed information about the minority carrier diffusion length with the only restriction being that the ratio D/L should be in the range 1-3 for exact measurements. The technique allows rapid assessment of the lateral variation of the diffusion length, in addition to the determination of the absolute value of the diffusion length at any spot.

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Implant Isolation of GaAs

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ABSTRACT

The ion species and dose dependence of implant-induced high resistivity regions in doped GaAs were investigated by Hall effect measurements, Rutherford backscattering, and secondary ion mass spectrometry. The initial conductivity of the GaAs is restored by annealing at 600°C, regardless of implant dose or species (O, F, or Ne), and the maximum resistivity in the material occurs for 500°C annealing. The temperature dependence of the carrier concentration in these samples shows the presence of several deep states responsible for the compensation effect.

High resistivity regions in doped GaAs can be produced by radiation damage resulting from the implantation of ions such as H^+ , B^+ , or O^+ (1-6). The compensation of the carriers in the material results from their trapping by deep level centers which are not thermally ionized at normal temperatures. This damage-induced isolation is widely used in device applications, including the fabrication of IMPATT diodes, field-effect transistors, stripe-geometry heterostructure lasers, avalanche diodes, and mixer diodes. Most of the isolation schemes in use are peculiar to

each particular process, and there are often differences reported in the efficiency of similar bombardment treatments in producing high resistivity material. This may be explained at least in part by surface conduction effects which are often overlooked, and the variation of the resistivity of the GaAs during subsequent low temperature processing steps.

In this paper we explore by Hall-effect measurements the ion species and dose dependencies of bombardmentinduced high resistivity GaAs, and their effects on the