Chapter 2

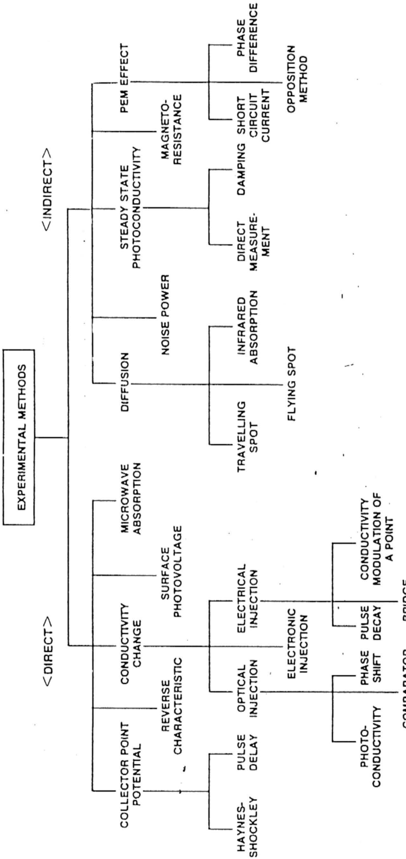
.0 Recombination lifetime characterization methods

Various experimental methods for lifetime measurements have been established. An experimental method to measure the lifetime requires injecting carriers into the sample by means of a flash of light or voltage pulses and observing their decay by any one of the following phenomena :

1. change in the potential of a collector point as a function of time,
2. reverse characteristics of p-n junctions,
3. conductivity change,
4. surface photovoltage effect,
5. microwave or infrared absorption,
6. diffusion,
7. photoelectromagnetic (PEM) effect,
8. steady-state photoconductivity,
9. shot noise and
10. magnetoresistance effect.

Experimental methods based on these phenomena can in general be classified into two categories as summarized in Fig. 2.3 [23]. The classification depends on whether the lifetime is measured directly as a time interval or indirectly through a related parameter like the diffusion length. The methods can also be separated into two broad categories. The first uses a sample of material as is and allows the lifetime

Fig. 2.3



Classification of experimental methods for measuring minority carrier lifetime of semiconductors. (PEM. photoelectromagnetic). (After Suryan and Silila.[19])

measurement nondestructively in which the samples are free of any mechanical or electrode contacts. The second makes use of the properties of a device in its final state which requires electrode contacts using p-n junctions or MOS capacitors.

When lifetime measurements are to be used to evaluate virgin material and the processes, those methods that require no additional sample preparation step are desirable. However, when lifetime measurement is for a sample in the form of a finished device, considerable caution must be taken in interpreting the material quality since the lifetime in finished devices is very sensitive to process conditions which may themselves introduce impurities and physical defects. The lifetime measurement techniques most commonly used for silicon are reviewed next.

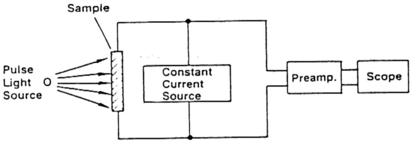
2.0.1 <u>Photoconductivity Decay Method</u>

In, this technique, the excess carriers are generated by illuminating the sample with a short pulse penetrating light. The conductivity σ of the sample is directly proportional to the number of carriers and the conductivity change is given by

$$\Delta \sigma = \Delta n \exp(-t / \tau_r)$$

Thus the minority carrier lifetime can be determined by monitoring the conductivity after illumination is removed. The photoconductive decay can be detected directly using ohmic contacts (technique used by ELYMAT) or indirectly by using microwave (technique used by μPCD) or infrared absorption techniques measuring eddy-current losses or capacitive coupling [24]. In Fig. 2.4 shows an experimental arrangement for the lifetime measurement using ohmic contacts. If the time

Fig. 2.4



Experimental arrangement for lifetime measurement using ohmic contact.

dependence of the excess carrier density is obtained from the display of the voltage change on an oscilloscope then, the analysis of the oscilloscope trace yields the sample minority carrier lifetime.

Generally in photoconductive decay method, surface recombination due to carrier trapping can seriously affect the measured decay curves. The temporary trapping of carriers superimposes a long lifetime constant tail on the exponential decay which results in a long lifetime than the actual one. For ordinary lifetime measurements, this effect can be minimized by using light with wavelengths near the absorption band edge, that is, with relatively low absorption coefficients, since the carriers are generated in the bulk of sample and not at the surface at all. The used of a filter made of the same material as the sample, interposed between the light source and the sample, is also useful to minimize the surface defect. The filter eliminates the short-wavelength nonpenetrating photons but passes a fair proportion of those wavelengths near the absorption edge which can be absorbed reasonably uniformly throughout the thickness of the sample. The bulk lifetime can be .calculated by subtracting the surface recombination velocity from the lifetime observed.

2.0.2 MOS Capacitor Method

Minority carrier lifetimes can be determined by observing the transient capacitance response of the metal insulator semiconductor (MIS) junction after the application of a large reverse-bias step. This lifetime measurement technique which is commonly called the MOS capacitance method is very useful for silicon wafers since a thin SiO_2 insulating layer can easily be grown on the surface. The physical terms, this method consists of applying a step voltage to the gate of an MOS capacitor in order to deplete majority carriers from the semiconductor surface. Initially a large depletion layer is formed. When the voltage is kept constant, electron-hole pairs are generated in the depletion region. The generation rate R_g, assuming most of the generation centers are located near the center of the forbidden gap, is approximately given by [25]

$$R_g = n_i / 2\tau_g$$

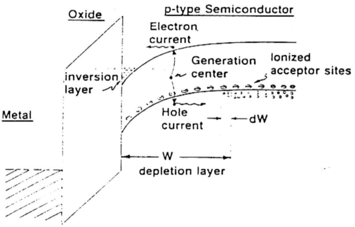
In a time t_r, enough carriers will be generated to neutralize the entire depletion layer width (W) :

$$R_g \, t_r \, W = [\,N\,]\, W$$
$$t_r = [\,N\,] / R_g = 2\,\tau_g \, ([N] / n_i)$$

where [N] is the doping concentration and $n_i = 1.4 \times 10^{10}$ cm^{-3} for silicon at room temperature. As minority carriers are generated in the depletion region, they are swept to the Si/SiO_2 interface where they accumulate in an inversion layer. The majority carriers generated flow to the edge of the depletion region where some of them neutralize the ionized impurity sites, reducing the width of the depletion region. The width of the depletion region thus decays as the inversion layer forms until equilibrium is reached. This phenomenon for p-type silicon is schematically shown in Fig. 2.5. Thus the MOS capacitor lifetime measurement method can be explained by the following procedure :

1. the gate bias is pulsed to a new value
2. the depletion layer width expands, and then
3. the decay of depletion width toward its equilibrium value is measured.

Fig. 2.5



Relaxation of depletion region due to generation of hole-electron pairs in the depletion region of MOS capacitor. (After Heiman.[31] © 1967 IEEE.)

Accordingly, this method consists of measuring either the MOS capacitance or the external current as a function of time. The procedure used practically to determine lifetime which was developed by Heiman [26] uses the recording of the normalized MOS capacitance versus time after the application of a large depleting voltage step, for example, positive for p-type semiconductor. Consequently, the minority carrier generation lifetime is calculated by the following equations :

$$t_r = [N] / R_g = 2 \tau_g ([N] / n_i) \quad \text{and}$$
$$\ln [(C_f / C - 1)/(C_f/C_o - 1)] + C_f/C - C_f/C_o = - (C_f/C_{ox})(t / t_r)$$

where

C_o	-	the initial capacitance
C_f	-	the final capacitance
C	-	transient capacitance
C_{ox}	-	oxide capacitance and
t	-	time

In practice, the lifetime is extracted from the C/C_{ox} versus t curve by writing

$$d\,C/dt = C^2 / t_r \, [1 - (C/C_f)]$$

Lifetime measurement tools / equipment

Several systems designed to monitor the wafer material quality and the contamination from various process steps in silicon IC processing have developed by various equipment manufacturers during the recent years. Methods based on minority carrier recombination behavior are attractivebecause of their high sensitivity, simplicity of sample preparation and short measurement times. The whole wafer mapping is possible with good spatial resolution in relatively short times. There is, however, considerable confusion of these characterization tools, concerning the capabilities and limitations of different systems in the market. There are several different types of measuring equipment for carrier recombination behavior in CZ silicon wafers, namely;

1. μ-PCDs by Leo Giken
2. Semilab and Semitex
3. Elymat by GeMeTec and
4. SPV by SDI.

In order to produce reliable semiconductor grade silicon, all considerable process media, process steps and intermediate product stages of wafering must be monitored by efficient analytical techniques. These analytical techniques must provide reliable, relevant and real-time results. There are only a few techniques satisfying these requirements.

In this section, we will look in detail on the two most common techniques commercially used i.e. μPCDs and Elymat. Both these techniques typically operate in high injection region where minority and majority carrier effects are intermixed.

2.1.1 μ<u>PCD</u>

Transition metal impurities have a detrimental impact on leakage current and gate oxide break down voltage and, therefore, on device yield and performance. Transition metals form recombination centers in semiconductor silicon. Thus, they act as effective minority recombination, or generation lifetime killers. Therefore, monitoring metallic impurities by lifetime measurements is of paramount interest in manufacturing semiconductor silicon devices.

The photoconductive decay technique, using the change of reflectivity of microwaves after pulsed optical excitation of excess minority carriers is a very convenient, i.e. non-destructive, contactless and fast way for the indirect in-line monitoring of metallic contamination in silicon. The decay of the reflected microwave signal gives direct information on the minority carrier recombination lifetime, that is a relevant electrical device parameter. The minority carrier recombination lifetime can vary from several microseconds for polycrystalline solar cells up to about ten milliseconds for high resistivity, high purity float zone material used as radiation detectors. Although the phenomena of μPCD were known for decades [27], recently , it has reattracted high interest due to the availability of automated and computerized equipment with both high lifetime resolution (0.1 μs) in a range of 0.1 - 10 μs and spatial resolution (1mm) [28].

The measured effective lifetime is always a superposition of bulk and surface recombination. The latter is usually not characterized by a lifetime value but by the surface recombination velocity. If the diffusion length of the carriers approaches the sample thickness, influences of both front and back side surface lifetime inhomogeneities can be seen. In most cases, however, the interest is focused on the bulk lifetime that can be obtained after passivation of both front and back side surfaces of the wafer against recombination.

The surface passivation can be achieved by two ways :

1. Passivation by thermal oxidation providing an oxide thickness of 20 nm. This method drives the surface impurities into the bulk.

2. Saturation of the surface states (" dangling bonds " - refer to Fig. 2.6) by dipping the wafer into an electrolyte such as a solution of HF or iodine tincture [29]. This method leaves the bulk contamination unaffected by the surface condition. A combination of both techniques on two halves of the same wafer allows separation of bulk and surface contributions.

To certain metals the recombination lifetime is not specifically sensitive. The meaning of a lifetime value, however, can be understood by simple correlation equation that has been established for the concentration of Fe (C) as a monitor element in B-doped CZ-Si [30] :

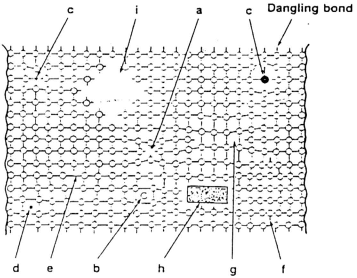
$$\tau\ (\mu s) = 10^{13} / C_{Fe}$$

Thus, a concentration of 10^{12} Fe at.cm^{-3} already limits the lifetime to 10 μs. The detection limit for metals is estimated to be about 10^{10} at.cm^{-3}. Similar results were found for Ti in specially grown B-doped CZ-crystals of Si [31].

Generally, the absolute lifetime values do not match well with the data that are obtained by other lifetime methods such as SPV or Elymat, because the injection level affects the recombination behavior [32, 33]. In process monitoring, however, absolute lifetime values are less relevant than their relative time stability. The defined time interval strongly depends on the process step to be monitored and can vary from several hours (e.g. the batchtime of cleaning baths) to months (storage time in a shipping carrier).

Due to the high spatial resolution by μPCD " hot spots " can be traced back to the cause of lifetime breakdown : Local spots for example can emerge due to contact with tweezers or transport belts. Large area inhomogeneities can be caused by

Fig. 2.6



Schematic diagram of various crystal defects in a simple cubic lattice contaminated gas flow or hot fluid process media. The maximum of information can be attained when at the " hot spots " lifetime methods are combined with tedious surface (TXRF) and bulk (DLTS) analytical techniques providing the identification of the contaminants.

2.1.2 Elymat

The Elymat technique is based on high resolution photocurrent imaging of silicon wafers applying diluted HF electrolyte contacts on both sides of the wafer [34, 35]. The electrolyte generates a large area Schottky-type contact and effectively eliminates the surface recombination. The front surface of the wafer is scanned with a laser beam with a maximum lateral resolution of 1 mm. The photocurrent is collected by reverse biasing either the frontside (FPC mode) or the backside (BPC mode) of the wafer. The bulk recombination can be detected only in BPC mode. Biased in the BPC mode, all minority carriers generated at the frontside of the wafer have to diffuse through the bulk for being detected at the backside. As for the BPC photocurrent, the incident laser beam intensity and the wafer thickness are the parameters needed to calculate the minority carrier lifetime and the minority diffusion length (L_D), L_D values in the range of 0.2 - 2 times the wafer thickness can be measured with high accuracy and precision.

Using the Elymat system, LOD (limit of detection) lies well below 10^{11} atom.cm^{-3} (FeB) in the bulk. Correspondingly, a surface concentration of Fe prior to the drive-in can be detected down to 10^{9} atom.cm^{-3}, if L_D is in the range of 1 mm or lifetimes above 300 μs [36].

The FPC mode probes the front surface layer only with the thickness of the surface layer depending on the wavelength applied. Therefore, in FPC mode very short diffusion lengths i.e. contaminated or precipitated wafers can be characterized. Particularly, the FPC mode may be applied for the detection of so-called haze-forming contaminants such as Cu and Ni [37].

Elymat measurements do not require any sample preparation. Wafers of p- or n-type (resistivity > 0.5 ohm.cm) with polished or etched surfaces can be measured. For a 200 mm wafer one Elymat-scan may takes about 15 min to generate an L_D-map of 1 mm resolution (a total of 2.5 x 10^4 pixels). After a drive-in anneal, the L_D-map exhibits the distribution of the surface metal contamination, allowing to track down contamination sources for example, by characteristic patterns. This imaging technique is an extremely helpful tool for equipment and process monitoring in silicon wafer manufacturing and device production. Furthermore, sources of crystal defects other than metal contamination, such as oxygen precipitates or slip line formation, can be readily identified by their characteristic lateral configuration. A more detail explanation on this technique will be discussed in next section.

Elymat wafer lifetime measuring technique

Wafer contamination by metallic trace impurities is well known to be a yield-limiting factor in semiconductor processing, gate-oxide integrity of CMOS-devices, refresh time performance of DRAMs, dark current of CCDs, and characteristics of low power and high power in bipolar transistors and diodes are influenced by metal contamination.

Metals in solution can act as generation and recombination centers limiting minority carrier lifetime. Future applications of silicon wafers will require increasingly higher levels of surface and bulk purity and minority carrier lifetime performance; the level of metal impurities must be well below the part-per-trillion range (ppt, $5\ 10^{10}$ atoms per cm^3).

The ELYMAT (Electrolytic Metal Analysis Tool) uses the minority carrier diffusion length imaging technique. The value of minority carrier diffusion length in a semiconductor has a simple relationship to minority carrier lifetime and is, as such, both a measure of crystal perfection and an important physical parameter in its own right.

ELYMAT identifies and maps the following classes of defects :

- Heavy metals (dissolved in the bulk or precipitated in the surface)
- Oxygen precipitates in the bulk or the surface layer
- Subsurface damage for example, from polishing.

The ELYMAT system is capable of measuring the local minority carrier diffusion length everywhere on a wafer. The high resolution capability results in a real and extremely useful images of the distribution of contamination in silicon wafers - often immediately pointing to its source - such as crystal pulling, cleaning, handling or high temperature processing.

Another advantage of ELYMAT is that no surface preparation is required when measuring bare wafers : minority carriers are generated by a laser beam which is scanned across the wafer surface. Contacts to the wafer are made by an electrolyte (1 % HF) on both sides. The electrolyte on the illuminated side eliminates surface recombination measurements, thus enhancing the sensitivity for bulk or near-surface recombination measurements. The electrolyte on the back-side provides a large area rectifying contact.

In the BPC (Back Photo Current) mode, minority carriers are collected by the backside contact and a photocurrent is measured as a function of the laser beam position. This photocurrent is modulated by the local density of recombination centers. Bulk contamination down to about 10^9 per cm^3 can be monitored in this mode.

The FPC (Front Photo Current) and DPC (Differential Photo Current) modes of operation give information about surface-near defects and surface recombination velocity respectively.

2.2.1 Principles

The followings give an overview of the basic principles of ELYMAT. Contamination by metallic trace impurities is a well known yield limiting factor in semiconductor processing. Metal impurities can be accidentally introduced into silicon wafers in many ways, during the various process steps in wafers manufacturing. Typical examples for contamination hazards are :

- handling, e.g. wafers in contact with metallic (or metal-contaminated) tools, carrier or transport systems, chucks ;
- wet processing, e.g. cleaning, etching ;
- dry processing, e.g. ion implantation, resist shipping, dry etching ;
- high temperature processing, e.g. oxidation, diffusion, drive in.

Minority carrier lifetime (i.e. the time constant for the decay of excess minority carriers generated by light or electrical injection) is one of the most important parameters in evaluating silicon material and devices. Minority carrier lifetime is extremely sensitive to small concentrations of metal impurities : the theoretical lifetime in pure silicon is in the order of hours, but it reduces to ≈ 10 ms for today's purest silicon crystals and to ≈ 100 μs for processed wafers with metal impurities such as Fe in the sub ppb range. Thus, the lifetime scales, in principle, with the wafer purity over a range of 10 orders of magnitude.

Crystal defects, such as single interstitial metal atoms or microscopic precipitates, generate energy levels in the silicon band gap, which enhance minority carrier recombination according to Shockley-Read-Hall theory (SHR). The recombination lifetime is inversely proportional to the defect concentration N:

$$\tau = \frac{1}{C_{eff}} \left(\frac{1}{N} \right) \qquad \text{Eqn. 2.1}$$

C_{eff} - effective temperature coefficient ; it depends on the chemical nature of the defect (energy level, capture cross section) and the injection level (concentration of excess minority carriers relative to the doping density).

The minority carrier diffusion length, L_D, is the mean distance minority carriers can travel between their generation by light or electrical injection and their decay. It is related to the lifetime τ through the relation

$$L_D = (D \bullet \tau)^{1/2} \qquad \text{Eqn. 2.2}$$

where D is the minority carrier diffusivity. For typical value of τ (1 μs to a few hundred μs), L_D varies from a few tens of μm to a few mm, thus exceeding wafer thickness.

The ELYMAT makes use of minority carrier diffusion length (or lifetime) measurements for detection and quantitative imaging of defects in silicon wafers. It is sensitive to metals and oxygen precipitates in the bulk or in the surface-near layer of the wafer. Surface impurities can be measured after activation by a thermal drive-in step (furnace annealing or RTA). With ELYMAT, concentrations of Fe as low as few times 10^{10} atoms per cm^3 (well below the ppt range) can be detected. For oxygen precipitates concentrations as low as 10^7 per cm^3 can be detected.

2.2.2 Working principles of ELYMAT

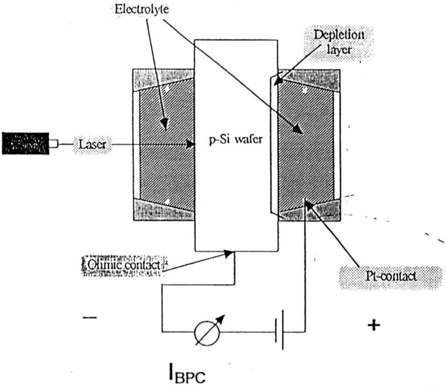
The heart of the ELYMAT is the electrolytical double cell. Figure 2.7 below shows the schematic for the most common mode of operation (BPC - Back Photo Current mode).

A wafer is inserted into an Electrolytical Double Cell and scanned by a focused laser beam on the front surface using a fast mirror scanner. The penetration depth of the laser is negligible compared with the wafer thickness, so that carriers are produced only in a thin layer near the surface. The diameter of the laser beam is less than 1 mm, which allows to scan with high resolution.

The silicon wafer is in contact with a suitable electrolyte on the frontside and backside. The wafer is electrically contacted by needles around the perimeter of the wafer ; the electrolyte by Pt electrodes. Both Si-electrolyte junction can be biased independently : in Fig. 2.7 is the electrolyte on the backside to be reversed-biased with respect to the needles.

As the laser beam scans the wafer, excess electron-holes pairs are locally generated in the front surface layer. During their diffusion through the wafer, minority carriers can recombine with the majority carriers at crystal defects (volume recombination).

Fig. 2.7



Electrolytical double cell: working configuration for the BPC

Minority carriers escaping recombination are collected at the biased Si-electrolyte junction (for the BPC mode - the backside junction), which acts as a large area and transparent Schotty contact : a depletion layer is formed which collects minority carriers.

The resulting current is measured for each scanned point. In this way a high resolution image of the defects distribution over the wafer can be obtained within a few minutes. A process competing with recombination of carriers at defects in the bulk of the wafer is their recombination at the surface, since the surface is by its very nature a giant defect in the periodic crystalline structure. This effect may dominate the overall recombination and thus strongly interfere with the lifetime measurements. In order to suppress surface recombination, the wafer is inserted into an electrolytical double cell so that during the measurement each wafer surface is in contact with a 1 % solution HF acid. The contact with the electrolyte produces the following effects :

- dissolution of the native oxide on the wafer surface ;
- saturation of surface states on the bare silicon surface through the formation of hydrogen bonds.

As a result in the BPC mode, the frontside electrolyte acts as reflecting boundary for minority carriers diffusing to the backside. With surface recombination absent, the reduction in the collected current with respect to the initial photocurrent is only a function of the number of defects along the path of minority carriers in the bulk of the wafer. Therefore, high photocurrent indicates high purity.

2.2.3 Modes of operation

2.2.3.1 BPC - Backside Photo Current mode

Defects in the wafer bulk can be detected in the BPC mode. This mode is sensitive to metals like Fe, Mo, Cr, Au and Pt which tend to form single atom recombination centers in the bulk of the silicon wafers.

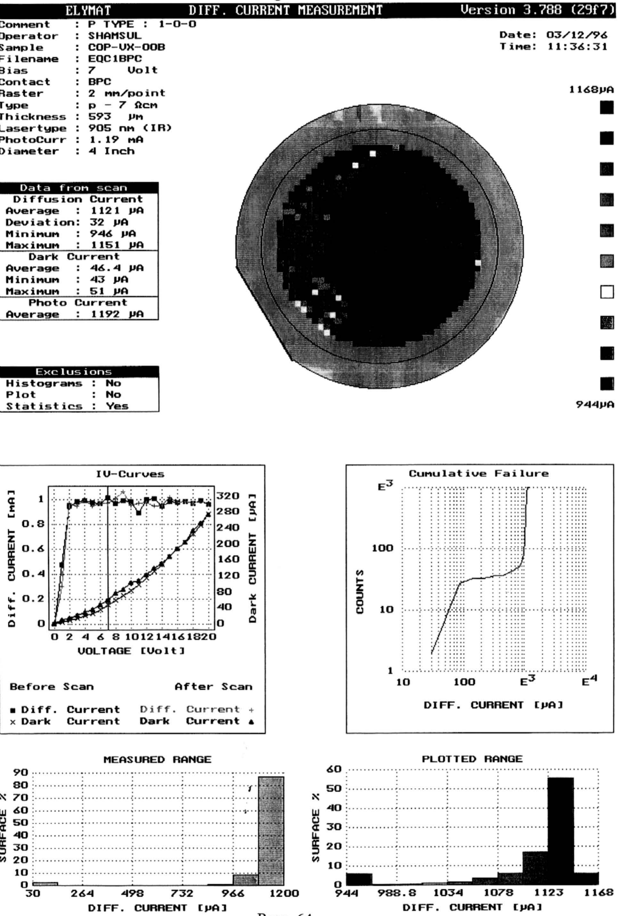
In the BPC mode the electrolyte on the backside is reverse-biased with respect to ohmic contact pins located in the wafer edge region. The electrolyte acts as a large area Schotty contact, that is, a depletion layer is formed which collects minority carriers diffusing from the frontside through the entire wafer thickness. The resulting backside photocurrent is measured for each scanned point.

In parallel with the measurement of backside photocurrent, the dark current measurement is perform i.e. the current flowing when the wafer is not illuminated by the laser. The dark current is determined by measuring the current at the backside with the laser beam illuminating a point outside the wafer (dark current point). This is to minimised measurement error of the backside photocurrent.

The dark current is subtracted point by point from the measured current in order to correctly evaluate the net photocurrent from the total measured current ; the resulting photocurrent values are recorded in a diffusion current map as shown in Fig. 2.8.

From Fig. 2.8 of the diffusion map, light color area represent contamination regions of the wafer and dark areas regions with high purity. Fig. 2.8 is an example of the results obtained for a typical ELYMAT measurement.

Fig. 2.8


ELYMAT DIFF. CURRENT MEASUREMENT Version 3.788 (29f7)
Comment : P TYPE : 1-0-0
Operator : SHAMSUL
Sample : COP-VX-00B
Filename : EQC1BPC
Bias : 7 Volt
Contact : BPC
Raster : 2 mm/point
Type : p - 7 Ωcm
Thickness : 593 μm
Lasertype : 905 nm (IR)
PhotoCurr : 1.19 mA
Diameter : 4 Inch
Date: 03/12/96
Time: 11:36:31
Data from scan
Diffusion Current
Average : 1121 μA
Deviation: 32 μA
Minimum : 946 μA
Maximum : 1151 μA
Dark Current
Average : 46.4 μA
Minimum : 43 μA
Maximum : 51 μA
Photo Current
Average : 1192 μA
Exclusions
Histograms : No
Plot : No
Statistics : Yes
1168μA
944μA
IV-Curves
Diff. CURRENT [mA]
Dark CURRENT [μA]
VOLTAGE [Volt]
Before Scan
After Scan
Diff. Current
Dark Current
Diff. Current +
Dark Current
Cumulative Failure
COUNTS
DIFF. CURRENT [μA]
MEASURED RANGE
SURFACE %
DIFF. CURRENT [μA]
PLOTTED RANGE
SURFACE %
DIFF. CURRENT [μA]

Besides the diffusion current map, important information such as I / V curve and the data concerning dark current were also obtained as output of the measurement. The dark current is an important result of the measurement which add additional information about the metals such as Cu and Ni, which would not be otherwise detectable from the BPC photocurrent : it has been proven that if the wafer is contaminated by Cu or Ni, a strong increment in the measured dark current is measured. Moreover, non ideal I / V characteristics ' leaky junction ' point to the presence of defects like metal silicide precipitates in the depletion region.

Figure 2.9 shows the correlation between metal concentration and dark current as measured by ELYMAT over a wide range of concentrations. The I / V curve represents the relation between the external voltage applied and the collected current. The laser beam is directed towards a point on the surface of the wafer chosen randomly by the software. The resulting photocurrent is collected applying an external bias which is let vary up to 20 V in 1 V steps. In each 1 V step, the dark current is also recorded (with the laser beam directed to a point outside the wafer surface). If the system is stable, the I / V curve does not significantly differ from the initial curve.

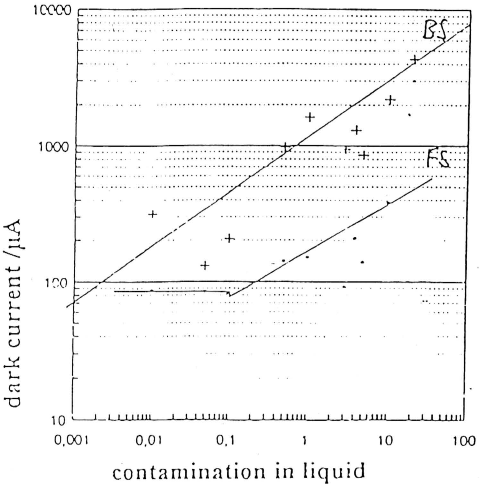
The diffusion current map can be converted into a diffusion length map; under the assumptions of negligible surface recombination and of small penetration depth of the laser, the backside photocurrent (I_{BPC}) is given by :

$$I_{BPC} = I_O / \cosh\left(\frac{d}{L_D}\right) \qquad \text{Eqn. 2.3}$$

where, I_O - total induced current (function of absorbed photon flux)

L_D - the diffusion length

Fig. 2.9



correlation between contamination from Cu and Ni and dark current measured by ELYMAT d - the wafer thickness

From the Eqn. 2.3 above, for the extreme case of diffusion lengths much larger than the wafer thickness ($L_D >> d$) all the induced photocurrent I_O is collected as backside photocurrent I_{BPC}. If $L_D \cong d$, I_{BPC} is reduced to 65 % of I_O. For $L_D = \frac{1}{2}d$ and $L_D = \frac{1}{3}d$, the values of I_{BPC} are reduced to 27 % of I_O respectively. If the level of contamination of wafer is such that the diffusion length is smaller than 20 % of the wafer thickness, a quantitative determination of diffusion length is not meaningful because the current at the backside is too small for evaluation. For these cases FPC (Frontside Photo Current) mode has to be used. If I_O is known, Eqn. 2.3 allows to calculate the diffusion length from the backside photocurrent. I_O can be determined by means of calibration. This can be performed using two different procedures :

1. FPC measurement of a wafer with the following characteristics :

   - its bulk diffusion length exceeds the wafer thickness ($L_D > d$);
   - The layer below the illuminated surface is free of defects: this condition can be fulfilled by chemical etching of the wafer to a depth where no damage is expected anymore.

   For such a wafer $I_{FPC} \approx I_O$; the FPC photocurrent can be used as calibration values.

2. One wafer is measured once in FPC and once in BPC mode; the diffusion length L_D is calculated from the ratio I_{FPC} / I_{BPC}, which is independent from I_O. The value I_O is then calculated from example, I_{BPC} and L_D.

Once I_O is known, the conversion of the measured backside photocurrent into diffusion length is performed by the software. A further conversion of the data allows to express the results in terms of excess minority lifetime using the Eqn. 2.1. The lifetime map obtained by conversion of the measurement is shown in Fig. 3.0.

2.2.3.2 Frontside Photo Current (FPC) mode

Defects in the surface-near layer can be detected by FPC mode. Again excess of carrier generation is produced by laser activation. As in the BPC mode, the low penetration depth of the laser light allows to generate minority carriers only near the illumination surface of the wafer. The basic configuration of the FPC mode is shown in Fig. 3.1.

For the FPC mode the contacts are the frontside electrolyte contact and the ohmic contact pins on the wafer edge. The collecting junction is on the illuminated side of the wafer : the minority carriers are not allowed to drift (and recombine) in the wafer bulk, so that the FPC mode is sensitive only to surface-near defects. In particular defects like Cu and Ni, which form near surface-precipitates, can be studied in the FPC mode. The information about silicyde precipitates is analogous to the chemical development of " haze " patterns, but it is more sensitive and obtained without etching.

In the FPC mode the following formula relates the measured frontside photocurrent I_{FPC} with the diffusion length, L_D.

$$I_{FPC} = I_O \left(1 - \left(e^{-\alpha x_P} \right) / (1 + \alpha L_D) \right)$$

Fig. 3.0

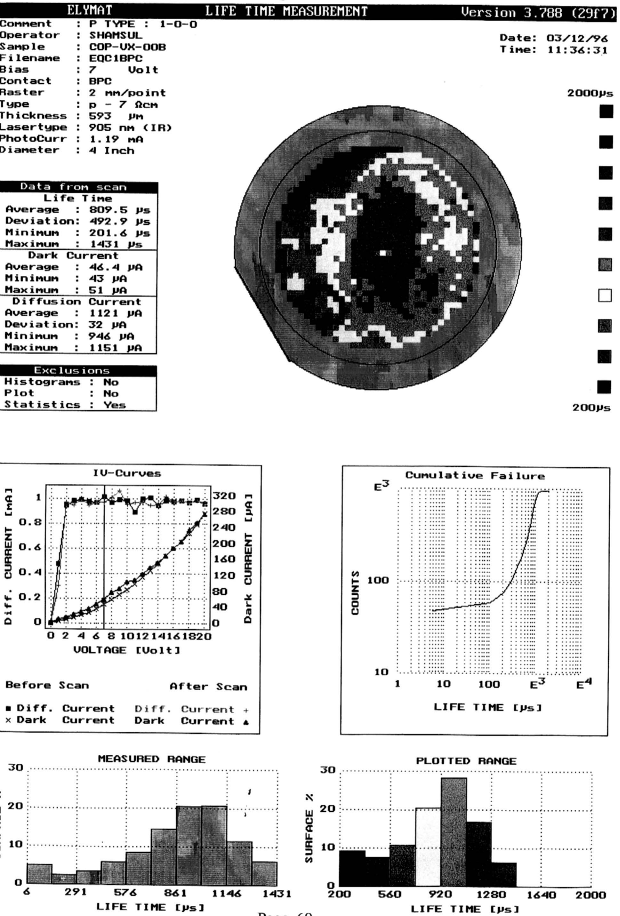
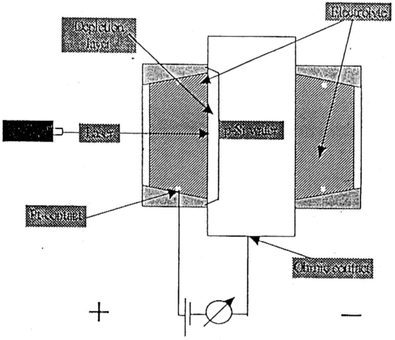

ELYMAT
LIFE TIME MEASUREMENT
Version 3.788 (29f7)
Comment : P TYPE : 1-0-0
Operator : SHAMSUL
Sample : COP-VX-00B
Filename : EQC1BPC
Bias : 7 Volt
Contact : BPC
Raster : 2 mm/point
Type : p - 7 Ωcm
Thickness : 593 µm
Lasertype : 905 nm (IR)
PhotoCurr : 1.19 mA
Diameter : 4 Inch
Date: 03/12/96
Time: 11:36:31
2000µs
200µs
Data from scan
Life Time
Average : 809.5 µs
Deviation: 492.9 µs
Minimum : 201.6 µs
Maximum : 1431 µs
Dark Current
Average : 46.4 µA
Minimum : 43 µA
Maximum : 51 µA
Diffusion Current
Average : 1121 µA
Deviation: 32 µA
Minimum : 946 µA
Maximum : 1151 µA
Exclusions
Histograms : No
Plot : No
Statistics : Yes
IV-Curves
Diff. CURRENT [mA]
Dark CURRENT [µA]
VOLTAGE [Volt]
Before Scan
After Scan
■ Diff. Current
× Dark Current
Diff. Current +
Dark Current ▲
Cumulative Failure
COUNTS
LIFE TIME [µs]
MEASURED RANGE
LIFE TIME [µs]
PLOTTED RANGE
SURFACE %
LIFE TIME [µs]

Fig. 3.1



basic configuration of ELYMAT for the FPC operation mode where α is the inverse of the laser penetration depth and x_P is the depth of the depletion layer.

The FPC mode can be conveniently used for highly contaminated wafers, which present diffusion lengths much smaller than the wafer thickness and can therefore not be measured in the BPC mode. Moreover, it also offers two different possibilities for the determination of the maximum photocurrent I_O.
As in the case of the BPC mode, also for the FPC mode the information about dark current is recorded, offering additional information about Cu and Ni contamination (DC mode). The FPC diffusion current map is shown in Fig. 3.2.

The FPC mode offers the possibility of studying the distribution of defects in 3-D, at least in the near surface of the wafer. A wide range of semiconductor lasers has become available in the recent years with colors ranging from green to infrared. Choosing the appropriate laser, the excitation depth can be varied, making it possible to extract depth information about the distribution of defects in the FPC mode. Important applications are in evaluating layered structures such as Epi and IG wafers (precipitate-free or denuded zone). In the next chapter, we will discussed the lifetime equipment used for this thesis and we will also look into real life measurements data on lifetime of bare silicon wafers.

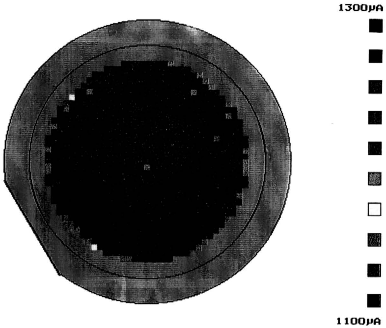
Fig. 3.2

ELYMAT DIFF. CURRENT MEASUREMENT Version 3.788 (29f7)

Comment : P TYPE : 1-0-0
Operator : SHAMSUL
Sample : COP-VX-00B
Filename : EQC1FPC
Bias : 7 Volt
Contact : FPC
Raster : 2 mm/point
Type : p - 7 Ωcm
Thickness : 593 μm
Lasertype : 905 nm (IR)
PhotoCurr : 1.19 mA
Diameter : 4 Inch

Date: 03/12/96
Time: 11:33:19

Data from scan	
Diffusion Current	
Average	: 1217 μA
Deviation:	9 μA
Minimum	: 1190 μA
Maximum	: 1258 μA
Dark Current	
Average	: 110.2 μA
Minimum	: 101 μA
Maximum	: 131 μA
Photo Current	
Average	: 1191 μA



Exclusions	
Histograms	: No
Plot	: No
Statistics	: Yes