Investigation of Silicon Defects Parameters in Electron Irradiated Diodes

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Introduction

The use of damage factors in semiconductors is of great practical interest. But they are only relevant for a given type of device or technology. Therefore, a minimum radiation testing has to be performed for each new technology generation or device type, in order to model the radiation response. On the other hand, the development of truly predictive tools is based on a thorough understanding of the fundamental radiation damage mechanisms. This could be done by analyzing energy values of electrically active levels and concentration of traps dose dependences, which could be measured by deep level transient spectroscopy (DLTS). This investigation determined and ranked the typical silicon irradiation defects.

Transient spectroscopy is widely used because of its high sensitivity, possibility to determine parameters of deep levels and can be adapted for ready-made devices or initial semiconductor. DLTS is often applied for features studies of deep impurities, irradiation defects and deep centres.

Investigative sample

As substrate was used standard n type float zone (FZ) silicon of crystallography plane (111). Thickness of silicon 400.0 ± 10 µm and substrate’s resistivity 150 ± 25 Ωcm were chosen to provide correct capacitance versus reverse voltage dependence and proper irradiation defects determination. Smaller dimensions of the sample (7×7mm) were selected to insure smaller junction capacitance.

Junction’s p+ region was formed by boron (BBr3) diffusion, which is 34.6 µm deep. Such boron diffusion depth is achievable only after next manufacturing operation – phosphorus diffusion that forms n+ region of cathode. Without previous operation boron diffusion was repeated twice. Sides were covered by aluminium layer (5.5µm) and ohm contacts were created.

![pn junction of the sample and electron beam direction](image)

Fig. 1. pn junction of the sample and electron beam direction

The whole structure of diode was electron irradiated from anode side, as shown in fig.1. Accelerator’s beam of electrons power is set to 10 MeV. Process passed at room temperature and irradiated samples from 100 kRad to 2.2 MRad dose.

DLTS measurement

The salient feature of DLTS is how transient signals are converted into a quasi-spectrum, as a function of temperature. In the original technique by Lang, the capacitance transient is measured at two fixed times \( t_1 \) and \( t_2 \) after the pulse and the signal \( C(t_1) - C(t_2) \) is measured. From Fig. 2 it is easy to see that when the temperature is varied, a peak-shaped signal will result [1]. In addition, it can be demonstrated that the peak maximum corresponds with a time constant \( \tau_{max} \), only defined by the selected instrumental times \( t_1 \) and \( t_2 \), namely:

\[
\tau_{max} = (t_1 - t_2) \left[ \ln \left( \frac{t_1}{t_2} \right) \right]^{-1}. \tag{1}
\]

The corresponding emission rate \( e_{max} = \tau_{max}^{-1} \) is often
called the emission rate window. Changing \( t_1 \) and/or \( t_2 \) will change \( e_{\text{max}} \) and hence the peak position \( T_{\text{max}} \), corresponding with a certain deep level \( \xi_T \). Repeating the temperature scan for different well-chosen rate windows, a set of peak maxima \( T_{\text{max}} \) can be obtained.

Uniform filling of level \( \xi_T \) is set by time constant \( \tau \), called relaxation time of the level filling. It can be finding from expression:

\[
\tau = r \cdot \exp\left(\frac{\xi_c - \xi_T}{kT}\right),
\]

where \( r \) – coefficient, depending on parameters of semiconductor and capture cross selection of electron to the level \( \xi_T \) – between conduction and valency band [2].

Therefore, \( \tau \) values are different for two deep centres of the same ionization energy. Relaxation time of the level filling does not depend on deep centre concentration and depends little on electric field. Ionization energy \( \Delta \xi_T = \xi_c - \xi_T \) and capture cross selection of electrons can be found out from dependence \( \tau(T) \).

According to expression (2) can be drawn \( \tau_{\text{max}} \) vs. \( 1/T_{\text{max}} \) in a so-called Arrhenius diagram.

For each deep level present in the material above a minimum concentration limit, one will obtain a DLTS peak. A spectrum generally consists of a series of peaks (in the temperature interval studied). For silicon, it goes from the freeze-out region (\( T=20-30 \) K) up to room temperature.

**Carriers’ traps spectrum analysis**

DLTS spectrum of investigated diodes has been measured at Vilnius University with spectrometer DLS-82E. Typical silicon diodes peaks were obtained by changing filter frequency of phase sinchrodetector and injection pulse length. Figure 3 illustrates spectrum peaks versus dose dependence, measured at the fixed DLS-82E parameters selection. From these dependences activation energies of carrier traps have been found: \( E_1=0.14-0.16 \) eV, \( E_2=0.23-0.24 \) eV and \( E_3=0.41-0.44 \) eV. They are attributed to vacancy-oxygen complex (\( E_1 \)), di-vacancy (\( E_2 \)) and vacancy-phosphorus (\( E_3 \)) complex – typical radiation defects.

There is separate filling relaxation time versus temperature dependence existing for each deep impurity level in the semiconductor. These dependences can be used as impurity typical feature. Unknown deep impurity is identified by comparison of its levels’ \( \tau(T) \) dependences with one of well known respective dependences.

**Fig. 4. Arrhenius plots for V-O (1), V\textsubscript{2}\textsuperscript{0\textsuperscript{-}} (2), V\textsubscript{2}\textsuperscript{0\textsuperscript{+}} (3) and V-P(4) traps, jointly with other traps library data**

Fig. 4 shows Arrhenius diagram, from which DLS-82E spectrum analyzer estimates array of trap: activation
energy, capture cross selection of majority carriers and
density of traps. Then it is easy to identify trap by
comparing with literature data obtained summarizing
various methods (FTIR, PL, EPR, DLTS, C-V and others).
For this purpose in DLS-82E is installed traps
identification library (Fig. 4).

DLTS peaks intensity has been recalculated by
 calibration absolute values of traps concentrations. When
irradiation dose is being increased, the vacancy-oxygen
and the vacancy-phosphorus complexes’ concentrations
approach the dopant concentration (Fig.5). Their trap
concentration forms about 10% of dopant (phosphorus, n-
Si) in diodes with the higher dose of irradiation.
Concentration of di-vacancy trap (V$_2^+$) is twice less than
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\[
N_{tr} = N_0 + \beta \Phi
\]

where $\Phi$ – electron irradiation dose, $N_0$ – defects
concentration for clean sample. Following $\beta$ values have
been calculated: for A-centre (V-O) $\beta_{V-O}=2 \times 10^9$
1/cm$^3$/kRad, for di-vacancy - $\beta_{V_2}=1.5 \times 10^8$
1/cm$^3$/kRad, for E-centre (V-P) $\beta_{V-P}=5 \times 10^8$
1/cm$^3$/kRad. Traps attachments (A and E) are matched with DLTS centres n-
Si nomenclature, as accepted in literature. Measured $\beta$
coefficients values have practical interest for studying silicon material. It is important for forecast of lifetime of
the carriers, leakage and current variations of non
combinative-diffused components.

It can be demonstrated that the A-centres are created
more efficiently by electron beam. Meanwhile, for di-
vacancy formation rather large primary vacancies
concentration is needed. Moreover, there is di-vacancy
creation activity barrier, which determines slower
generation of di-vacancy. Direct generating of di-vacancies
by irradiation with electrons is less expected. Complexes
of phosphorus and vacancy are created slower than oxygen

complexes too. It is the way of the oxygen concentration,
which even in FZ silicon is greater (>10$^{16}$ cm$^{-3}$) than
dopant (N$_{dop}$, p $\approx$ 3 $\times$ 10$^{13}$ cm$^{-3}$).

Points scatter in $N_{tr}$(\(\Phi\)) dependence for E-centre
is large, as in range of this peak forms additional peak,
increasing the electron irradiation dose. This additional
peak is well seen in fig. 5 at the 2200 kRad dose curve and
its Arrhenius plot is given in fig. 4. This peak is
intersecting with E-centre plot and it is well known in
DLTS n-Si spectroscopic literature. But there still exists
some controversy in the literature about the exact position
of the acceptor level $V_0^+$ (for p-type silicon it should be
$V_0^+$ donor level) for which values are reported at around
$E_v + 0.20$ eV or $E_v + 0.24$ eV [3].

![Fig. 5. Traps concentrations given for various irradiation doses](image)

Defects creation versus dose dependences have been measured by calibrating traps concentration for peaks, as
shown by figure 6. Coefficient $\beta$ of defects creation rate
allows scheduling defects concentration by formula:

\[
N_{tr} = N_0 + \beta \Phi
\]

where $\Phi$ – electron irradiation dose, $N_0$ – defects
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![Fig. 6. Defects creation rates versus dose](image)

This additional centre ($E_a$) in DLTS radiation defects
nomenclature is also known as marking „170”, attached to
the peak temperature domination, that is to 170K. Defect
originates at large doses area and often is interpreted as
peak of radiation defects cluster.

However, to our mind, summarizing deeper and wider
DLTS spectrum analysis for Si formations irradiated with
various particles, more acceptable interpretation for
additional „170” centre is related to di-vacancy duplex. It
means that together with $V_2^{0+}$ peak (at 120 K) at larger
temperature range (~170K) di-vacancy centre of another
electric state $V_2^{0-}$ appears.

Concentrations of these $V_2^{0+}$ centres are close to $V_2^{0-}$
centres density but smaller than E-centres concentration.
Therefore, this $V_2^{0+}$ peak is highlighted from E-centres density.

Conclusions

1. DLTS spectrum for investigated diodes with
different irradiation dose has been obtained. Carriers traps
activation energies, attributed to vacancy-oxygen, di-
vacancy and vacancy-phosphorus complexes have been
estimated. It was established that these are the main defects
consequences the pn junction dynamics in silicon.
2. Defects Arrhenius diagram, for obtaining other trap parameters: capture cross selection of majority carriers, activation energies and traps densities, has been made. Arrhenius diagram also allows calculating of the relaxation time of the energy level filling and thus to control the lifetime of the carriers.

3. Irradiation dose dependence plots for diodes have been drawn out of measured main carriers’ traps concentrations. Traps creation rates according to initial impurities concentrations have been evaluated. Therefore, the oxygen-vacancy complexes have the fastest creation in FZ silicon.

4. Defects formations coefficients versus dose dependences have been obtained and their creation rates coefficients have been calculated. It has practical interest for studying silicon material.

5. Additional centre of radiation defects was obtained at large doses, related to di-vacancy duplex. Thus, was calculated the minimum generation dose of this defect and its activation temperature.

References


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