Physica B 407 (2012) 2998–3001

Contents lists available at SciVerse ScienceDirect

Physica B

journal homepage: www.elsevier.com/locate/physb

Study of irradiation induced changes of electrical and functional characteristics in Ge doped Si diodes

E. Gaubas [a,*], A. Uleckas [a], J.M. Rafi [b], J. Chen [c], D. Yang [c], J. Vanhellemont [d]

[a] Institute of Applied Research, Vilnius University, Sauletekio 9-III, LT-10222 Vilnius, Lithuania
[b] Centro Nacional de Microelectrónica (IMB-CSIC), Campus UAB, 08193 Bellaterra, Spain
[c] State Key Laboratory of Silicon Materials, Zhejiang University, Hangzhou 310027, China
[d] Department of Solid State Sciences, Ghent University, Krijgslaan 281 S1, B-9000 Ghent, Belgium

ARTICLE INFO

Available online 26 August 2011

Keywords:
Defects
Irradiation hardness
Ge doping
Czochralski silicon

ABSTRACT

P-on-n diodes fabricated on n-type Cz Si wafers with different Ge doping concentrations were irradiated with 2 MeV electrons and 1 MeV equivalent reactor neutrons using a wide range of fluences and examined by combining current and capacitance transient techniques.

1. Introduction

Defect engineering by specific doping and irradiation technologies is one of the possibilities to improve and modify specific parameters of semiconductors devices [1,2]. It is known that Ge doping of Si during the Czochralski (Cz) growth process has a beneficial effect on reduction of dislocation nucleation and being an isovalent impurity it does not introduce electrically active deep centres [3,4]. Therefore, it is a promising dopant for the expedient manipulation both of the internal gettering capacity and of the intrinsic point defect incorporation during crystal growth. In this work, n-type Cz grown Si diodes containing different Ge doping concentrations and irradiated using a wide range of 2 MeV electron and 1 MeV eq. reactor neutron fluences have been investigated by combining deep level transient spectroscopy (C-DLTS), barrier evaluation by linearly increasing voltage (BELIV) pulsed transients and small ac signal *C–V* as well as dc *I–V* techniques.

2. Samples and measurement techniques

Three sets of Si diodes processed on n-type Cz wafers have been investigated, two of them with Ge doping concentration of about 10^{19} cm^{-3} and 10^{20} cm^{-3} (GCz and GGCz), respectively, and the third one without Ge doping (Cz). The density of majority carriers of 1.5×10^{14} cm^{-3} Cz Si material of diode base layer is determined by P dopants. P-on-n diodes were irradiated with 2 MeV electrons as well as with reactor neutrons using fluences in the range of 10^{12}–10^{17} cm^{-2}.

Examination of the diodes has been performed by combining several techniques. C-DLTS spectroscopy has been used to identify specific irradiation induced defects and to evaluate the parameters of deep centres in order to reveal the impact of Ge doping.

Barrier capacitance charging and charge extraction currents together with space charge generation currents have been examined using the barrier evaluation by linearly increasing voltage (BELIV) pulsed technique [5]. This allows extracting of parameters of effective doping, of dielectric relaxation time and of carrier generation lifetime. Current transients are registered with an Agilent Technologies DSO6102A oscilloscope using a 50 Ω load input. Additionally, the measurement circuitry contains an adjusted output of a generator of linearly increasing voltage (LIV) and the diode under investigation, connected in series. The other channel of the digital oscilloscope is used for synchronous control of the linearity of the LIV signal using a signal differentiating procedure installed within the DSO oscilloscope. The transient of the total reverse current at reverse polarity of the LIV pulse can be described by a sum (i_Σ) of barrier charging-charge extraction (i_C) and generation (i_g) current components [5]:

$$i_\Sigma(t)=i_C(t)+i_g(t)=AC_{b0}\frac{1+(U_C(t)/2U_{bi})}{(1+U_C(t)/U_{bi})^{3/2}}+\frac{en_iSw_0}{\tau_g}\left(1+\frac{U_C(t)}{U_{bi}}\right)^{1/2}.$$

Here, $A=\mathrm{d}U(t)/\mathrm{d}t\cong U_P/\tau_{PL}$ is the ramp of the LIV pulse with a peak voltage U_P and duration τ_{PL}. $C_{b0}=C(t=0)$ is the barrier capacitance determined by the built-in barrier U_{bi}. w_0 is the depletion width in the diode of junction area S, τ_g is carrier generation lifetime within the space charge region and n_i is the intrinsic density of

* Corresponding author. Tel.: +370+52366082.
E-mail address: eugenijus.gaubas@ff.vu.lt (E. Gaubas).

0921-4526/$ - see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.physb.2011.08.056

carriers. $U_C(t) \cong At$ is the voltage drop over the diode, which linearly increases with time (t). An advantage of the BELIV technique is the possibility to resolve the barrier capacitance at rather low applied voltages of a single polarity and to separate the time dependant generation current above a barrier depletion one. This technique is preferable due to small voltage changes during the LIV pulse and due to a constant displacement (A) induced by the external LIV. The BELIV technique also enables to separate the barrier capacitance at reverse and forward small voltage biasing. The reverse biased BELIV transient contains an initial peak, which is related to the equilibrium barrier capacitance C_{b0}, followed by a decreasing component of the charge extraction capacitance and an increasing component attributed to generation current. Such a set of current components of the reverse biased BELIV current transient, implies the existence of a current minimum within a transient, which can be highlighted by varying the LIV pulse duration or using additional steady-state illumination.

These BELIV characteristics were correlated with characteristics measured using small ac signal C–V and dc I–V techniques. The combined analysis of the BELIV, C–V and I–V characteristics is used to evaluate the role of the dielectric relaxation time changes and of the series bulk resistance in the heavily irradiated diodes, containing different densities of Ge doping.

3. Results and discussion

Typical C–V characteristics, measured on the non-irradiated diodes are plotted in Fig. 1(a) as C^{-2} vs. voltage function, indicating the high doping densities in the Ge containing material. This result is corroborated by analysis of the BELIV transients (Fig. 1b) measured on the same diodes. As illustrated in Fig. 1(b) (left-bottom scales), a clear increase of the barrier capacitance (barrier charging current measured on 50 Ω load resistor) with increasing Ge doping density is observed. The extracted doping density, which is the sum of the dopants and the thermal donors is shown in Fig. 1(b), right-top scales, as a function of Ge concentration.

Four peaks related to radiation induced defects, all majority carrier trapping centres, have been observed with DLTS in both types of samples in the temperature range of 80–280 K [6]. A peak around 85 K is attributed to the V–O centre (with activation energy $E = E_C - 0.177$ eV and cross-section $\sigma = 10^{-14}$ cm^2 as evaluated from Arrhenius plots [6]), a peak associated with $V_2^{=/-}$ is situated at 137 K ($E = E_C - 0.233$ eV, $\sigma = 10^{-15}$ cm^2 [6]) in agreement with widely accepted DLTS results [7]. The peak at 175 K ($E = E_C - 0.355$ eV, $\sigma = 7 \times 10^{-15}$ cm^2 [6]) is associated with multivacancy (V_n) complexes [8,9] while the divacancy ($V_2^{-/0}$) ($E = E_C - 0.425$ eV, $\sigma = 10^{-15}$ cm^2 [6]) in single charged state is revealed by the peak at 240 K [10]. Only slight variations of the radiation induced defect density are observed due to Ge doping when comparing spectra obtained for electron irradiation fluences below 10^{15} cm^{-2}. V–O centre is dominant at low irradiation fluence, but its DLTS peak decreases with electron irradiation fluence while the one associated with the single charged divacancy becomes dominant. Such changes in DLTS spectra are strongly affected by the free carrier redistribution among deep traps of different species. Due to the lack of free carriers to fill the high density of radiation defects, the deepest centres govern the capture of doping induced carriers with an associated increase of the space charge generation current in the temperature range above 150 K. The influence of Ge doping manifests itself by a slower reduction of the density of V–O centres in GCz material for the range of small and moderate irradiation fluences, when comparing to Cz diodes. The densities of the various traps extracted from DLTS as a function of electron irradiation fluence are shown in Fig. 2(b).

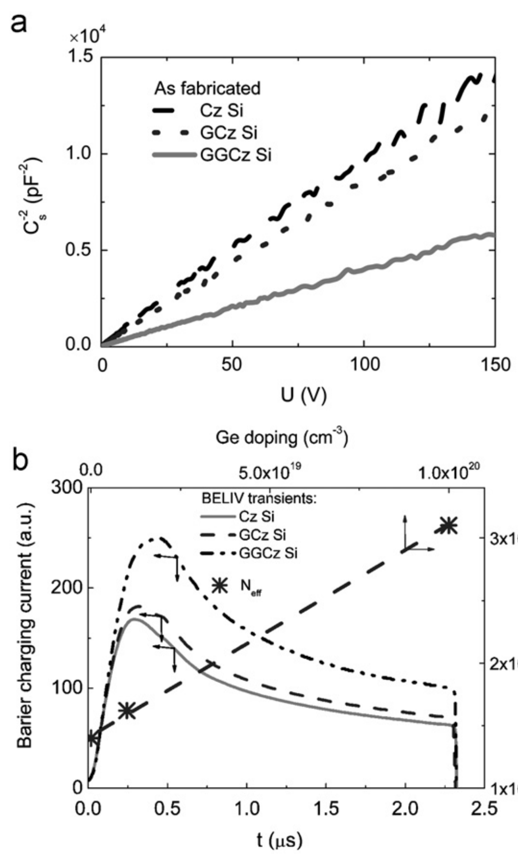

Fig. 1. Reciprocal capacitance (C^{-2}) vs. voltage (a) and barrier capacitance charging current transients (b) dependant on Ge doping density measured on non-irradiated Cz, GCz and GGCz diodes. In (b), right-top scale, the extracted doping density as a function of Ge doping is shown.

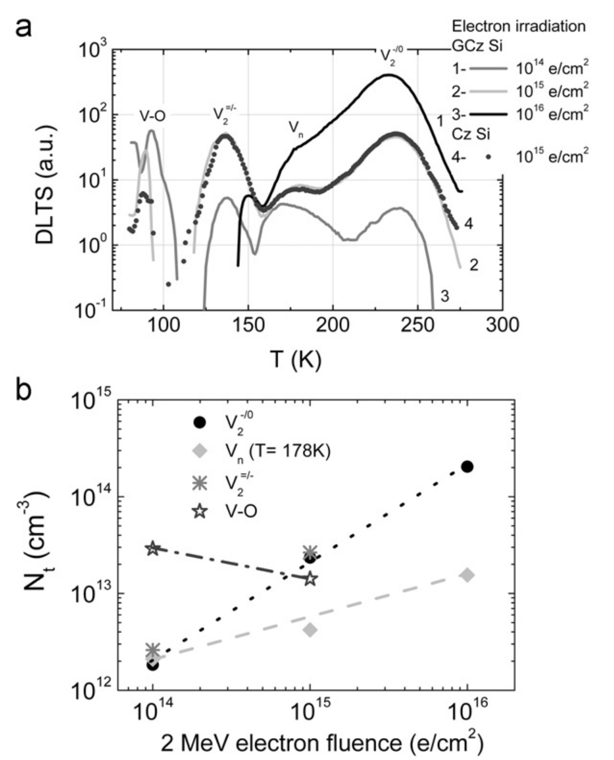

Fig. 2. (a) DLTS spectra of Cz (solid line) and GCz (symbols) Si diodes after irradiation with 10^{14}–10^{16} cm^{-2} electron fluence. (b) Fluence dependant variations of density of various traps.

The leakage current, extracted from the *I*–*V* characteristics, increases nearly linearly (a slope is close to unity within log–log scale) with 2 MeV electron fluence in the range of 10^{14}–10^{16} cm^{-2}, as shown in Fig. 3(a). The leakage current is smaller in GCz diodes before irradiation compared to that in Cz diodes. After electron irradiation, the leakage current increases and does not depend noticeably on Ge doping. The forward current also increases with irradiation fluence (for fluences below 10^{16} cm^{-2}) due to the enhancement of the recombination current component. However, for irradiation fluences above 10^{16} cm^{-2}, the injection capability of the forward biased diode drops and a forward current is obtained to be smaller than that in less irradiated diodes. This result can be explained by the increase of the serial resistance in the bulk of material [4], due to a reduction of the majority carrier density.

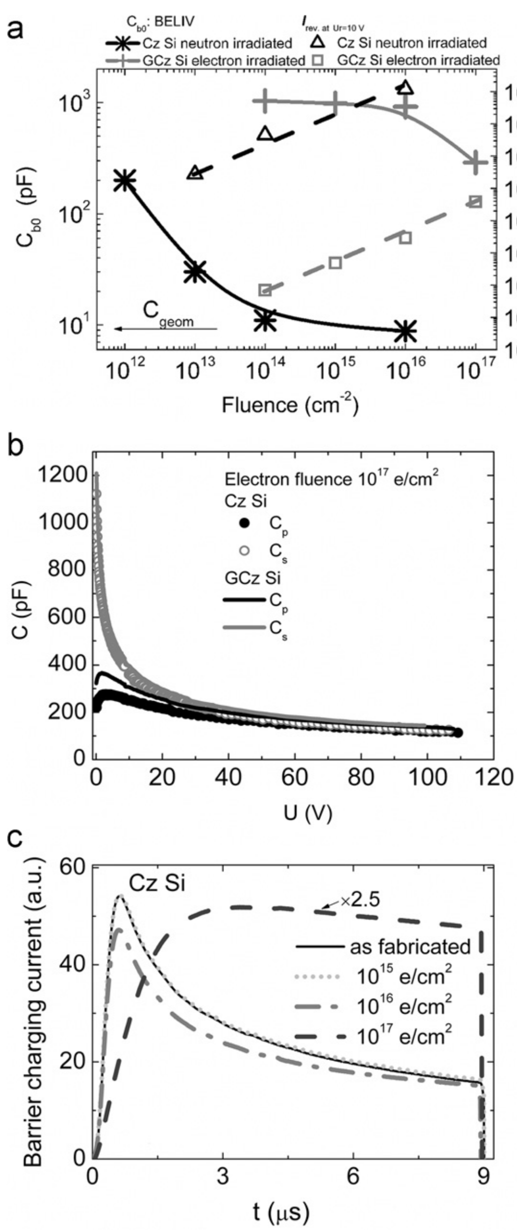

Fig. 3. (a) Variations of leakage current and barrier capacitance charging currents dependant on electron and neutron irradiation fluence in Cz diodes. (b) Comparison of the *C*–*V* characteristics in 10^{14} and 10^{17} e/cm^2 irradiated diodes, obtained using small ac signal LRC technique varying parallel (C_p) and series (C_s) measurement regimes. (c) Fluence dependant variations of barrier capacitance charging current transients.

The small ac signal *C*–*V* characteristics measured at 100 kHz show clear deviations in *C*–*V* characteristics measured by LRC-metre using parallel (C_p) and series (C_s) regimes (Fig. 3b) only for the 10^{17} cm^{-2} electron irradiated diodes. These deviations indicate that the generation current leads to erroneous capacitance data only for the heaviest electron irradiations. While for neutron irradiated diodes, the space charge generation current disturbs the LRC capacitance measurements already for neutron irradiation fluences below 10^{14} cm^{-2}. Variations of the *I*–*V* and *C*–*V* characteristics (Fig. 3b) qualitatively correlate well with the variations of the BELIV transients (Fig. 3c). The barrier capacitance charging/carrier extraction current (which is proportional to the value of the BELIV signal) transients show a clear decrease of the barrier capacitance with increasing irradiation fluence.

A comparison of the barrier capacitance changes in neutron and electron irradiated Cz Si diodes is presented in Fig. 3(a). For Cz Si diodes, the barrier capacitance drops to the geometrical capacitance value after neutron irradiation with fluences above 10^{15} n/cm^2. This indicates that the material changes from a semiconductor to an insulator after heavy neutron irradiations. A significant decrease of the barrier capacitance in 2 MeV electron irradiated diodes is observed only for fluences close to 10^{17} e/cm^2. The reduction of the barrier capacitance as a function of the irradiation fluence correlates well with the increase of the leakage (actually, space charge generation) current. The values of the leakage current in neutron irradiated diodes exceed those observed in electron irradiated diodes by more than three orders of magnitude, while the leakage current shows a linear increase with fluence after both types of irradiations.

The enhancement of leakage current together with the reduction of the barrier capacitance complicates simple *C*–*V* and DLTS measurements. The leakage current disturbs the current phase shift measurements using LRC-metres (Fig. 3b), while an increase of trap density and a lack of free carriers control the filling of the deepest traps and the observation of the generation current peak filtered within the DLTS response (Fig. 2).

The barrier capacitance values in GCz and GGCz Si diodes, compared to Cz Si diodes, show that Ge doped material is radiation hard up to electrons fluences of 10^{16} e/cm^2. The heaviest (10^{17} e/cm^2) irradiated diodes, however, show a significant decrease of the barrier capacitance (Fig. 3c). As a consequence, the barrier charging current exhibits a decrease and a delay for GCz Si diodes irradiated with electrons of 10^{17} e/cm^2 fluence, which is due to the lack of free carriers, when the density of radiation induced traps starts to prevail.

4. Summary

The combined analyses of Cz, GCz and GGCz Si diodes indicate increased effective doping densities in the Ge containing material, caused by the enhanced formation of thermal donors. Single charged divacancy becomes dominant in DLTS spectra after irradiation with electrons of fluences above 10^{15} e/cm^2 when redistribution of carrier capture flows among deep traps of different species appears. The deepest centres govern the capture of doping induced carriers leading to an increase of the space charge generation current. The influence of Ge doping, manifests itself by the slower reduction of density of *V*–*O* centres in GCz Si diodes, relative to Cz Si diodes. The barrier capacitance drops to the geometrical capacitance value for Cz Si diodes after neutron irradiation with fluences above 10^{15} n/cm^2. This indicates that the material goes from semiconducting to insulating state after heavy neutron irradiation. A significant decrease of the barrier capacitance in 2 MeV electrons irradiated diodes is observed only for fluence values close to 10^{17} e/cm^2. The leakage currents in neutron irradiated diodes exceed those observed in electron irradiated diodes by more than three orders of magnitude, while a linear increase of the leakage current with fluence is observed after both types of irradiations.

Acknowledgement

The authors would like to acknowledge the contributions of their colleague and friend Prof. Hidenori Ohyama who sadly passed away in beginning of 2011 in the course of our collaboration.

References

[1] B.Y. Baliga, Power Semiconductor Devices, PWS Publishing Company, Boston, 1995.
[2] P. Hazdra, V. Komarnitskyy, Microelectron. J. 37 (2006) 197.
[3] C.A. Londos, A. Andrianakis, V.V. Emtsev, H. Ohyama, Semicond. Sci. Technol. 24 (2009) 075002.
[4] J. Vanhellemont, J. Chen, J. Lauwaert, H. Vrielinck, W. Xu, D. Yang, J.M. Rafí, H. Ohyama, E. Simoen, J. Cryst. Growth 317 (2011) 8.
[5] E. Gaubas, T. Ceponis, J. Vaitkus, J. Appl. Phys. 110 (2011) 033719.
[6] J. Chen, J. Vanhellemont, E. Simoen, et al., Phys. Status Solidi C 8 (2011) 674.
[7] B.G. Svensson, M. Willander, J. Appl. Phys. 62 (1987) 2758.
[8] R.M. Fleming, C.H. Seager, E. Bielejec, G. Vizkelethy, D.V. Lang, J.M. Campbell, J. Appl. Phys. 107 (2010) 053712.
[9] V.P. Markevich, A.R. Peaker, S.B. Lastovskii, L.I. Murin, J. Coutinho, V.J.B. Torres, P.R. Briddon, L. Dobaczewski, E.V. Monakhov, B.G. Svensson, Phys. Rev. B 80 (2009) 235207.
[10] J.H. Bleka, L. Murin, E.V. Monakhov, B.S. Avset, B.G. Svensson, Appl. Phys. Lett. 92 (2008) 132102.