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Physica B 308–310 (2001) 357–360

PHYSICA B

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Erbium excitation across the bulk of silicon wafer: an effect of p–n junction at Si/Si:Er interface

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Abstract

It is known that emission from Er ions implanted into a silicon wafer can be excited by illumination of the non-implanted side of the sample. In such a configuration, energy has to be transferred across the entire thickness of the sample (300–500 μm), which exceeds by two orders of magnitude absorption depth of a 514.5 nm line of an Ar ion laser. We have shown that for the non-implanted side illumination configuration, the energy transfer process leads to a delay in the onset of Er photoluminescence signal, whose magnitude depends on the excitation power. In the present contribution, we investigate the microscopic mechanism responsible for this delay. We postulate that it can be related to exciton dissociation at a p–n junction created by Er doping at a Si/Si : Er interface. We confirm this hypothesis by showing that the actual value of the delay time can be tuned by a bias voltage applied to the junction. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Photoluminescence; Silicon; Erbium

1. Introduction

Erbium doping of silicon has recently become an extensively studied subject. The rare-earth erbium, when incorporated in silicon in the trivalent charge state, shows characteristic luminescence from an intra-4f transition at a wavelength of 1.54 μm. This emission can be observed both under optical or electrical excitation. This optical doping technique seems to be a promising way around the problem of the indirect band gap of silicon. If sufficiently high Er concentrations could be incorporated and activated, it would become possible to fabricate light emitting diodes, lasers, or optical amplifiers, based on silicon. This would enable the integration of optical and electronic technologies on the same chip. Therefore, a thorough understanding of the microscopic process responsible for the energy transfer between the crystalline silicon matrix and the 4f-electron core of Er ions is of prime importance.

Some time ago it was reported that Er PL can be generated from the Er-implanted crystalline silicon wafer under conditions when the laser beam operating in the visible region is pointed at the non-implanted side of a wafer [1]. In such a configuration, excitation is absorbed at a distance of 350–500 μm from the Er-doped layer. Careful investigation [2] showed that PL spectra obtained under implanted and non-implanted side excitation were identical in their structure. Therefore, the same optically active centers are excited in both experimental configuration, i.e., excitation diffusion across the bulk of the material does not influence the "final" excitation mechanism responsible for the energy transfer to the rare-earth ion core. From the measurements of the kinetics of the process, it has been found out that for the non-implanted side excitation, the Er-related PL signal appears with a considerable delay of the order of a few milliseconds with respect to the excitation pulse. The actual magnitude of this delay was

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0921-4526/01/$ - see front matter
PII: S0921-4526(01)00699-8

found to depend on the laser power. While the appearance of Er-related PL upon the backside illumination is normally attributed to long-range exciton diffusion, the observed long delay time was inconsistent with that model. Taking into account the appropriate material parameters, i.e., exciton life time and diffusion constant, a delay of a few microseconds can be expected, clearly at variance with the experiment.

In the current contribution, we explore the exciton dissociation at a p–n junction at Si/Si : Er interface as a possible mechanism responsible for the observed delay. We report that the actual value of the delay time can be changed by bias voltage applied to the junction.

2. Experimental

The experimental configuration used in this study is illustrated in Fig. 1. It allowed for an easy change between excitation of either the implanted side or the backside of the sample, while a DC voltage (−10 to +10 V) could be applied by electrical contacts on both surfaces. In both excitation modes, PL was collected from the Er-implanted side. The experiments were performed in a closed cycle cryostat in the temperature range between $T \approx 15$ and 150 K. An on–off modulated (25 Hz) argon laser operating at $\lambda = 514.5$ nm was used as an excitation source. The emerging PL signal was monitored with a high-sensitivity germanium detector (Edinburgh Instruments).

The investigation was conducted for a low-energy (300 keV, 3×10^{12} cm^{-2} dose) Er-implanted oxygen-rich p-type (B-doped) Cz–Si wafer of approximately 350 μm thickness. The sample was also co-implanted with oxygen (40 keV, 3×10^{13} cm^{-2} dose) and annealed at 900°C in a nitrogen atmosphere for 30 min.

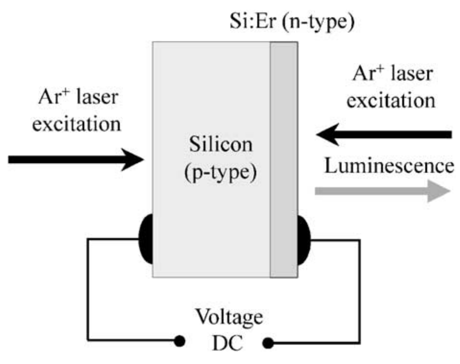

Fig. 1. Experiment allowing for excitation either of surface of the sample or electrical bias. Photoluminescence is detected from the Er-implanted side of the sample.

3. Results and discussion

For the sample used in the investigations, a strong PL spectrum was observed under different excitation conditions. Fig. 2 compares PL spectra obtained with and without electrical bias. As can be seen, spectral structure is not influenced by the bias and conclude that the same Er-related optical centers are activated under conditions of different electrical bias, as used in the present study.

We will first consider the case of excitation by a green laser pointed at the wafer side opposite to the Er-implanted layer. In this case, the relevant parameters are as follows: photon energy $h\nu = 2.4$ eV, absorption coefficient $\alpha = 10^4$ cm^{-1}, and pumping intensity $I = 3 \times 10^{16}$ cm^{-2} s^{-1}. To analyze the exciton diffusion at distance s, we should solve the diffusion equation with a source of excitons near the surface ($x = 0$)

$$\frac{\partial N_{ex}}{\partial t} = D\frac{\partial^2 N_{ex}}{\partial x^2} - \frac{N_{ex}}{\tau_{ex}} + \alpha I g(t)\exp(-\alpha x) \quad (1)$$

for a continuous pumping

$$\frac{\partial N_{ex}}{\partial x} = 0 \quad \text{at } x = 0. \quad (2)$$

From this, we can get the exciton density flux $j_{ex}(x,t) = -D\partial N_{ex}/\partial x$ at $x = s \gg \alpha^{-1}$ [3,4]:

$$j_{ex}(s,t) = \frac{I}{\sqrt{\pi}}\int_0^{t/\Delta t} dz\,\frac{1}{z^{3/2}}\exp\left[-\left(\frac{1}{z} + \frac{s^2}{4L^2}z\right)\right]. \quad (3)$$

Here N_{ex}, D, and τ_{ex} are the exciton concentration, diffusion coefficient, and the exciton lifetime, respectively. We introduce parameter $\Delta t = s^2/4D$ and the diffusion length of the excitons $L = \sqrt{D\tau_{ex}}$. The parameter Δt determines the diffusion-related time delay, i.e., the time necessary for an exciton to arrive at distance s due to diffusion. For a reasonable parameter value of $D = 90$ cm^2 s^{-1} [5], the time delay $\Delta t = s^2/4D$ due to diffusion for the distance of

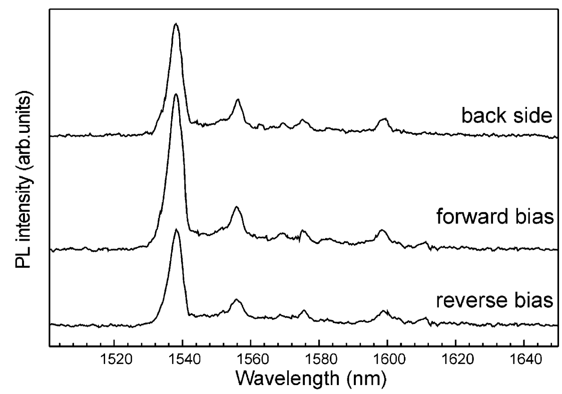

Fig. 2. PL spectra obtained for non-implanted side excitation with and without electrical bias.

$s \cong 350\ \mu m$ is about $3.5\ \mu s$, which is two order of magnitude faster than observed in the experiment.

Having excluded exciton diffusion across the silicon wafer as a possible reason for the long delay time observed in appearance of PL signal, we will now consider change accumulation at Si/Si : Er interface as an alternative mechanism. Indeed, it is generally accepted [6] that erbium implantation into oxygen-rich silicon leads to the formation of donor centers with ionization energies in the 0.1–0.25 eV range and concentration comparable to that of Er ions. Since the sample under investigation was prepared from p-type Si ($[B] = 10^{15}\ cm^{-3}$) and the Er concentration in the implanted layer is $\sim 10^{18}\ cm^{-3}$, a p–n junction should occur in equilibrium at the boundary with the Er-implanted layer. The excitons arriving at the p–n junction will therefore experience the electric field related to the depletion layer formation. In this field, whose value can reach 10^4 V/cm, the exciton will be divided into electrons and holes. These will gradually accumulate at a junction lowering the potential. Excitons will start to appear in the Er-doped layer and excite Er only after the depletion region has been removed due to charge compensation. We can expect that this effect can be influenced by biasing the junction. As illustrated in Fig. 3, the actual delay time can indeed be reduced under the forward bias condition, the effect being very similar to the earlier reported delay reduction upon increase of excitation density [2]. Fig. 4 shows in detail how the experimentally measured delay time can be turned by the electrical bias applied to the junction. For the purpose of this experiment, contacts were made with silver paste on the opposing faces of the sample, which was then placed in the low-temperature experimental set-up allowing for measurements in the two illumination configurations. In addition, DC voltage from a stabilized power supply could now be applied, providing electric field across the thickness of the sample. Prior to the PL experiment, we measured the low-temperature I–V characteristics of the sample. The result, also depicted in Fig. 4, confirms that Er implantation into a p-type silicon substrate results in p–n junction formation. We then proceeded to investigate the PL signal delay time in the backside illumination configuration and under the applied bias. While the Er-related PL spectrum did not change (see Fig. 2), the kinetics of the signal were clearly influenced by the bias. As can be seen, under conditions of reverse bias the delay time can be increased as the depletion region increases; the delay time can be brought down to zero under forward bias. Following our interpretation, the applied forward bias reduces the depletion region to a level at which excitons diffusing towards the Er-implanted layer are no longer destroyed.

In order to evaluate quantitatively if the junction effect can account for the observed delay, we have to estimate the time necessary to compensate the change in the depleted region. The width of the depletion region is controlled by boron doping, and at low temperatures is given by

$$W \cong \sqrt{\frac{\varepsilon(E_g - (E_D + E_B)/2)}{2\pi e^2 N_B}}, \qquad (4)$$

where E_g is the energy gap, E_D and E_B are the binding energies of the Er-related donors and boron acceptors, respectively, e is the electron charge, and ε is the dielectric constant of silicon. The calculated depletion region of about 1 μm is situated predominantly in the p-type layer. The negative charge ($-N_B W$) is accumulated in the depletion region of the p-type layer, and the same positive charge ($+N_D W_D = N_B W$) is in the n-type layer.

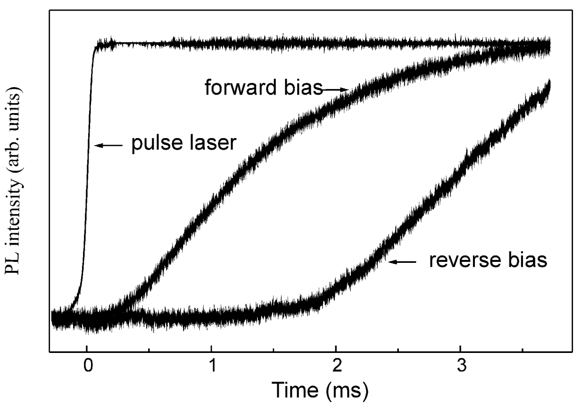

Fig. 3. Time development of the Er-related PL signal under non-implanted side excitation with electrical bias. The laser pulse is also shown.

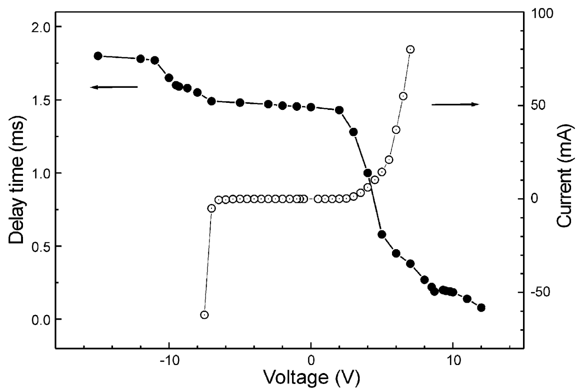

Fig. 4. Delay time of the Er PL observed for non-implanted side excitation as a function of electrical bias, and I–V characteristics of the (p-type) sample used in the experiment.

The time δt which is needed for the destruction of the p–n junction can be found from the equation

$$\int_0^{\delta t} \mathrm{d}t\, j_{\mathrm{ex}}(s,t) = N_{\mathrm{B}} W, \tag{5}$$

where $j_{\mathrm{ex}}(s,t)$ is given by Eq. (3). Assuming the fast diffusion process, we can use the equilibrium formula for finding the delay time δt

$$\delta t \frac{\sqrt{\pi}}{2\sqrt{2}} I \exp(-s/L) = N_{\mathrm{B}} W. \tag{6}$$

From here the diffusion length L can be estimated. With the experimentally obtained value of the delay time δt in the millisecond range, we get $L \approx 60$ μm. Such a diffusion length corresponds to an exciton lifetime of $\tau_{\mathrm{ex}} \approx 0.4$ μs. In our experiment, the lifetime of the free excitons is controlled by capture at neutral boron acceptors. This assumption is supported by the observation of bound exciton luminescence for non-implanted side excitation. In this case, we have

$$\frac{1}{\tau_{\mathrm{ex}}} = N_{\mathrm{B}} \sigma_{\mathrm{ex}} \langle v \rangle, \tag{7}$$

where $\langle v \rangle$ and σ_{ex} are the thermal velocity and capture cross-section of free excitons, respectively. The calculated exciton lifetime corresponds to $\sigma_{\mathrm{ex}} \approx 1.2 \times 10^{-15}$ cm^2, which is a reasonable value. Therefore, we conclude that the presence of the p–n junction can lead to the observed delay time.

4. Conclusions

The characteristic $\lambda = 1.54$ μm emission of Er^{3+} ions implanted into a silicon wafer is excited by an Ar laser pointed at the non-implanted side of the sample. In this experimental configuration, energy is transferred across the bulk of a Si wafer before reaching the Er-doped layer. It is found that the exciton diffusion across a p–n junction created by Er doping at the Si/Si : Er interface leads to a considerable delay between the excitation pulse and the appearance of Er-related PL. This is caused by the time necessary to accumulate charge to compensate the voltage at the junction and prevent dissociation of arriving excitons. It is shown that the particular value of this delay time can be changed by application of electric bias to the junction. Results of the research confirm that excitons are responsible for Er excitation in crystalline silicon at cryogenic temperatures.

Acknowledgements

This work was supported by grants from NATO (Linkage) and Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO).

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