Light Emission and Charge Trapping in Er Doped Silicon Dioxide Films Containing Silicon Nanocrystals


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Er implanted SiO$_2$ films have recently attracted considerable interest due to the possibility of making EL devices that operate at a wavelength of 1.54 µm, i.e. within the range of optical transparency of quartz optical fibers [1, 2]. The fabrication of such light emitting devices is fully compatible with Si based integrated circuit (IC) technology, thus permitting their integration into advanced Si ICs. Critical issues of the device performance are the relatively low emission efficiencies and the low currents that can be passed through the dielectric. It has been shown in a number of studies that the introduction of Si nanocrystals into Er-doped SiO$_2$ enables the intensity of the PL at 1.54 µm to be largely increased [3-5] while causing concurrently a somewhat reduced EL intensity [6]. However, the mechanism of attenuation of the Er associated EL at 1.54 µm after introducing Si nanoclusters into the SiO$_2$ matrix has not been elucidated. The present work provides new insights into the relationship between light emission efficiency and charge trapping in Er doped SiO$_2$ containing Si nanoclusters. The influence of the Si nanocluster density on both the capture of charge carriers at traps associated with the presence of Er and the resulting PL and EL at 1.54 µm is examined for the first time.

Si wafers with a 200 nm thick thermally grown SiO$_2$ film were used in the study. The depth profiles of the implanted Si$^+$ and Er$^+$ ions were calculated using TRIM 98 as a first approximation. Si$^+$ ions were implanted at two implantation energies of 35 and 80 keV, which generated a fairly flat-topped profile of 1.1 to 15 at.% excess silicon atoms over a depth region of 65 to 150 nm. After annealing at 1100°C in an N$_2$ ambient for 1 h necessary to form Si nanocrystals, Er$^+$ ions were implanted at 280 keV with a dose of $1 \times 10^{15}$ cm$^{-2}$ in such a way as to position the peak of their distribution about the central part of the Si clusters profile. Finally, the samples were annealed at 850°C in an ambient of N$_2$ for 30 min to reduce the amount of the implantation induced damage and activate the implanted Er$^{3+}$ centers. The top electrodes were 100 nm indium-tin-oxide (ITO) layers patterned into circular dots with a diameter of 0.05 to 1.00 mm.

The formation of Si nanoclusters and Er$^{3+}$ centers were monitored by PL measurements over the wavelength range of 600 to 900 nm and at 1535 nm using the 532 nm line of a Nd:YAG laser and the 633 nm line of a He-Ne laser with a power of 5 mW as the excitation sources, respectively. Measurements of the EL and charge trapping were carried out in a high field, constant current injection regime. Charge traps were studied over a wide range of cross sections using three levels of injected constant current density, namely $1 \times 10^{-7}$, $2 \times 10^{-5}$ and $5 \times 10^{-4}$ A cm$^{-2}$, with the last value of the current density being typical of the regime of EL excitation. During the current injection, negative (or positive) charges were trapped within the oxide layer, which caused a decrease (or increase) in the electric field distribution at the Si/SiO$_2$ interface. In order to maintain a constant current injection, one needs to shift the applied voltage as the trapped charges change. Charge trapping processes were studied under conditions of electron injection from the Si substrate into the oxide by measuring the shift of the applied voltage with the injected charge $Q_{inj}$. The absolute value of the net trapped charge was calibrated using the shift of the flat band voltage, $\Delta V_{FB}$, extracted from the high frequency (1 MHz) capacitance-voltage ($C-V$) characteristics after injecting an electron charge of $1 \times 10^{13}$ e/cm$^2$.

Figure 1(a) shows EL spectra measured over the wavelength range of 1450 to 1650 nm in Er implanted structures containing Si nanocrystals of different density. The peak at 1535 nm, which is characteristic of the intra-transition of the electron in the Er$^{3+}$ ion from the excited $^4I_{15/2}$ state to the ground state, is clearly seen. A broad PL peak centered at 700 nm was observed as a result of the introduction into the oxide of an excess of Si atoms above 3 at.%. The position of the PL peak
Fig. 1: (a) Electroluminescence (EL) spectra of the ITO-
SiO₂-Si structures with SiO₂ containing Si nanoclusters and
Er; (b) PL and EL intensity at 1535 nm wavelength and PL
intensity at 707 nm wavelength in dependence on excess Si
content. The relative PL intensity of the emission peak of the Si
nanocrystals and the peak at 1535 nm due to the
presence of Er³⁺ ions are shown in Fig. 1(b). One
can see that the increase in Si nanocluster density
results in an increased PL intensity of the infrared
peak from Er³⁺. A maximum value is observed at
the excess Si content of 10 at.%. In contrast, the
EL intensity at 1535 nm is strongly quenched at
such an excess silicon concentration. It should be
noted that the intensity of the infrared EL
diminishes strongly with decreasing the average
distance between the silicon clusters below the
mean free path of the hot electrons (or heat up
distance), which equals to approximately 3 nm [8].
Our calculations show that for Si nanoclusters with
a mean size of 3 nm, the average distance between
the nanoclusters becomes smaller than 3 nm for an
excess Si content of more than 5 at.% (see
Fig. 1(b)). Thus the average energy of the elec-
trons will decrease with increasing the fraction of
direct tunneling among the silicon nanoclusters.

It should also be noted that in our case EL
from Si nanoclusters has not been observed at the
currents and voltages used, up to the breakdown of the
dielectric. This can serve as evidence of the
ineffective excitation of the Si nanoclusters by the
high energy injected electrons. Due to the inefficient
excitation of silicon nanoclusters, the EL
from the Er centers can not be efficiently excited
through the strong energy transfer from the excited
silicon clusters to the Er centers compared with the
PL excitation processes.

The current density, \(J\), versus inverse electric
field, \(E\), was plotted in Fowler-Nordheim (FN)
coordinates (\(\ln(J/E^2) - 1/E\)) for different values of
the excess Si content as shown in Fig. 2. The cha-
acteristics so obtained reveal that up to a 3 at.%
excess Si content the current injection through the
dielectric can be described by the Fowler-Nord-
heim electron tunneling mechanism [9]. For a
higher concentration of the excess Si atoms of
5.6 at.%, the effective potential barrier for FN
tunneling decreases from 3.15 to 2.90 eV. This
points to the influence of trapping on the electron
tunneling through the triangular potential barrier
from Si to the SiO₂ conduction band, the so-called
trap-assisted tunneling mechanism [10]. At a
higher excess Si content the transition from FN
tunneling to direct tunneling between silicon
clusters can be clearly seen (Fig. 2).

The dependence of the trapped charge on the
injected electron charge is shown in Fig. 3. The
starting unimplanted oxide exhibits practically no
trap-assisted tunneling following electron injection at a
charge density of \(10^{13} \text{e}/\text{cm}^2\). After the same
amount of injection the Er⁺ implanted sample
shows considerable positive charge trapping. This
indicates the presence of hole traps with a giant
cross-section (\(\sigma_h > 10^{-13} \text{cm}^2\)) in the Er-implanted
oxide. The subsequent introduction into the Er-
implanted oxide of Si nanoclusters results in
additional electron trapping and points towards the
formation of negative charge traps with a giant
cross-section (\(\sigma_e > 10^{-13} \text{cm}^2\)). Furthermore, an
increase in the Si nanoclusters density up to 15% is
accompanied by an increased magnitude of the
trapped negative charges (see inset to Fig. 3).

Computer data processing of the \(C_{DXX}AV_{CC}\) vs.
\(Q_{inj}\) curves was done on the basis of the model for
the first order charge carrier trapping [11, 12]:

\[
Q_i = Q_{i,\text{max}} \left[ 1 - \exp\left(-\sigma_i Q_{inj}\right) \right],
\]

where \(Q_i\) and \(Q_{i,\text{max}}\) are respectively the trapped
and the maximal trapped charge at the \(i^{th}\) trap,
and \(\sigma_i\) is the cross-section of the \(i^{th}\) trap. The most
important findings may be summarized as follows. The starting structure exhibits only hole traps with cross-sections $\sigma_{h1} \approx 6.2 \times 10^{-15}$ cm$^2$, $\sigma_{h2} \approx 1.2 \times 10^{-15}$ cm$^2$ and $\sigma_{h3} \approx 4.7 \times 10^{-17}$ cm$^2$. The implantation of Er, apart from hole traps of a giant cross-section ($> 10^{-13}$ cm$^2$), introduces into the oxide an appreciable concentration of electron traps of a large cross-section ($\approx 10^{-14}$ cm$^2$), which may lead to Coulomb scattering of the injected electrons and attenuation of their interaction with the Er centers around them. Since the excitation of the Er through the excitation of the Si clusters is not efficient in the EL process, we suggest that Er excitation is mainly due to direct impact excitation of hot electrons [13], which are accelerated by the high electric field in the SiO$_2$ conduction band after FN tunnelling injection from the Si substrate. The scattering of hot electrons by both the charged defects and the Si nanoclusters results in a reduction of the average energy and the average impact excitation across the Er centres around the negatively charged nanoclusters. Increasing the Si nanocrystal density (for concentrations of the excess Si larger than 5 at.%) alters the conductance from FN tunnelling to direct tunnelling through silicon clusters. The tunnelling electrons have insufficient energy to excite Er centres, which subsequently reduces the EL efficiency.

The defect influence on the product of the effective electron lifetime ($\tau$) and the effective cross-section of excitation ($\sigma$) can be estimated from the dependence of the EL intensity on current density [6] in Fig. 4. As can be seen from the inset to Fig. 4, the value $\sigma\tau$ decreases about seven times with increasing excess Si content from 1.1 to 15 at.%. In a study [3] of the dependence of the Er luminescence decay time on the excess Si concentration from 2.4 to 11 at.% after annealing at the same temperature of 1100°C, the lifetime of the Er-induced PL was found to decrease only by a factor of about 2 (from 4.4 to 2.1 ms). This means that the excitation cross section of Er was reduced by a factor of more than 3 in the EL excitation by introducing Si clusters with an excess Si content of up to 15 at.%. Such different behavior of the PL and EL depending on the Si nanocrystals density is associated primarily with the different nature of the excitation in the vicinity of the Er$^3^+$ ion. In the PL excitation process, the excitation of Er occurs via naturally charged exciton relaxation created in the Si nanoclusters, which does not alter significantly...
the electric field around the Si nanocrystals. In the EL excitation process, electrons trapped at the Si nanoclusters act repulsively to the hot electrons for excitation of both of the nanoclusters and the Er centers in the surroundings. This could be one of the reasons for the insufficient excitation of both the EL from nanoclusters and the Er centers with introducing discrete Si clusters. The larger the number of the Si nanocrystals surrounding an Er inclusion, the more efficient screening of the electric field among the clusters occurs, which is essential for the heating of electrons. Consequently, in considering the excitation of Er ions by electrons passing through an amorphous SiO$_2$ layer, one should take into account their interaction with the defect environment of the Er inclusions.

In conclusion, it has been found that the introduction of Si nanocrystals results in the creation of negative charge traps of a giant cross-section, which can scatter efficiently “hot” electrons. Higher concentrations of the Si nanoclusters alter the mechanism of current passage through the dielectric. In this case, electrons are most likely transported in the SiO$_2$ via Si nanocluster mediated tunnelling, and therefore they interact very little with the Er inclusions.

The presented results have been recently published as A. Nazarov et al., Appl. Phys. Lett. 86 (2005) 151914.

References