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Room temperature light emitting silicon diodes fabricated by erbium ion implantation

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Abstract

In this work we report the fabrication and characteristics of light emitting erbium-doped Si diodes operating at room temperature (RT). These devices were prepared by multiple high energy Er implantation in the active region of a p^+–n^+ Si diode. Oxygen or fluorine implantation in the Er-doped region was also performed in order to properly modify the Er^{3+} chemical surrounding. Electroluminescence (EL) at 1.54 μm and at RT has been observed under both forward and reverse bias conditions with the maximum intensity under reverse bias. The temperature dependence of the luminescence revealed that forward-bias EL decreases by about a factor of 30 on going from 100 K to 300 K. An identical temperature dependence is observed in photoluminescence (PL) suggesting that similar excitation mechanisms are responsible for PL and forward-bias EL. In contrast, reverse-bias EL presents a very weak temperature dependence, with a decrease by only a factor of 4 from 100 K to 300 K. These data are reported and possible excitation mechanisms are discussed.

1. Introduction

Optoelectronics and integrated photonics is a rapidly expanding field in view of a more efficient telecommunication technology. In particular, the capability of combining, within a single chip, optical and electronic devices represents one of the major goals still to be achieved. Being silicon by far the most used semiconductor in the microelectronics industry, a Si-based optoelectronics would certainly contribute to reach this goal.

Several approaches have been recently followed to obtain light out of silicon [1]. Among these Er doping seems particularly promising [2–12]. Erbium ions, when in their 3+ state, can emit photons at 1.54 μm due to an intra-4f shell transition. This wavelength is particularly appealing for the telecommunication technology since it corresponds with a window of maximum transmission for the optical fibers. When inserted in the Si host matrix Er^{3+} ions can be excited via electron–hole (e–h) mediated processes and hence light emitting silicon diodes can be conceived [3]. Several problems are however inherent to the Er:Si system. For instance, the luminescence has been seen to be very low in Er implanted pure float-zone Si [5] even at low temperatures, demonstrating that either a small fraction of erbium is in the optically active 3+ state or only a small fraction of erbium can be actually pumped through e–h recombinations. Moreover, the luminescence intensity presents a strong temperature quenching and is seen to decrease by about 3 orders of magnitude on going from 77 K to room temperature [4,5]. Impurity co-doping has been shown to play a crucial role in modifying the Er chemical surrounding [6] thus enhancing the Er luminescence [7] and strongly reducing its temperature quenching [8]. This has recently allowed to produce light emitting Er-doped Si diodes operating even at room temperature [9,10].

In this paper, we present the preparation and performances of light emitting silicon diodes formed by Er ion implantation and impurity co-implantation. The possible mechanisms producing luminescence will be also discussed.

2. Experimental

Er-doped p^+-n^+ light emitting silicon diodes were realized as follows. Epitaxial n-type (7 Ω cm) silicon layers (20 μm thick) were grown on top of (100) oriented heavily n-type doped (10^{-2} Ω cm) substrates. These samples were implanted by 40 keV B to a dose of $5 \times 10^{15}/cm^2$ to produce a surface p^+ layer. The n^+ region was subsequently realized in the epitaxial layer by 2 MeV

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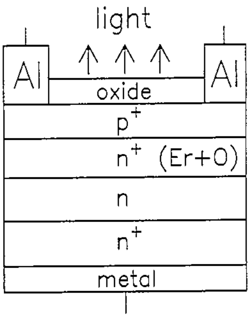

Fig. 1. Schematic cross section picture of the light emitting silicon diode.

5×10^{15} P/cm^2 implantation. Er was introduced in the active region of the device by several implants in the energy range 0.5–5 MeV performed by the 1.7 MV Tandetron of the CNR-IMETEM Laboratory in Catania. These implants produced a constant Er doping at a concentration of 1×10^{19}/cm^3 between 0.3 and 1.8 μm. In order to properly modify the chemical environment of the Er ions these samples were then implanted by O or by F in the energy range 0.15–1.4 MeV to produce constant concentrations of 1×10^{20}/cm^3 of these species in the Er-doped region .

All of these implants produced a continuous amorphous layer extending from the surface to a depth of 2.3 μm. After implantation samples were then annealed at 620°C for 3 h in N_2 atmosphere to induce the epitaxial crystallization of the amorphous layer. A further thermal annealing at 900°C for 30 min in N_2 flux with a partial pressure of O_2 was subsequently performed to activate the dopants and to grow a thin surface oxide layer (50 nm) to passivate the Si surface. Finally, aluminum patterns were photolithographically defined on the samples allowing some open area for the exit of the light.

A schematic drawing of the light emitting silicon diode is reported in Fig. 1. All of the features described above are clearly visible. Current–voltage characteristics in the temperature range 100–300 K showed that this diode is, under forward bias, always in the recombination regime. Moreover, the reverse bias characteristics are almost temperature independent and present a breakdown voltage of ~ −5 V (due to the Zener effect).

Electroluminescence (EL) measurements were performed by biasing this diode with a square pulse at 55 Hz. The EL signal was collected by a lens, analyzed by a monochromator and detected by a liquid nitrogen cooled

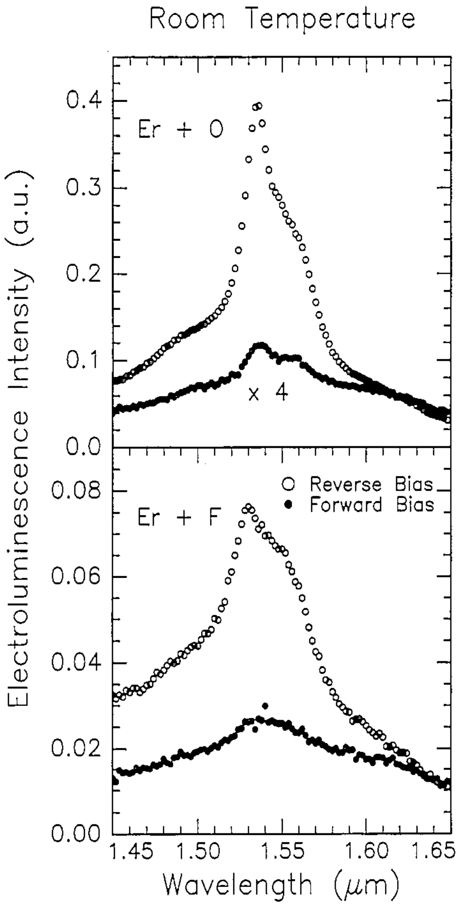

Fig. 2. Room temperature electroluminescence spectra under forward bias (●) and reverse bias conditions (O) for the Er+O doped device (upper part) and for the Er+F doped device (lower part). The spectrum of the Er+O diode under forward bias conditions is multiplied by a factor of 4. The spectra are taken at a constant current density of 2.5 A/cm^2.

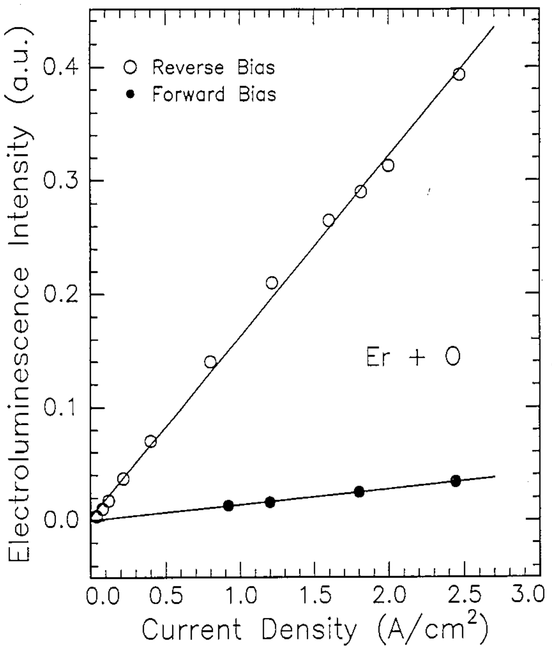

Fig. 3. Room temperature current density dependence of the electroluminescence intensity under both forward and reverse bias conditions. The continuous lines are guides to the eye.

Ge detector. Spectra were recorded using a lock-in amplifier with the voltage pulse as a reference.

3. Results and discussion

Room temperature EL spectra in Er + O and Er + F doped silicon diodes are reported in Fig. 2. The spectra refer to a constant current density of 2.5 A/cm^2 through the device under both forward (closed circles) and reverse bias conditions (open circles). Under forward bias a weak, but clearly visible, peak at around 1.54 μm is observed both in O- and F-doped samples (with the peak slightly higher in the oxygen case). Interestingly, under reverse bias conditions in the breakdown regime a much more intense EL peak is detected. This peak is about 20 times higher than under forward bias with an identical current density. Moreover, it is 5 times higher in the O-doped sample with respect to the F-doped one. The shape of the spectra in the two cases (O and F co-doping) is also slightly different suggesting that light emission arises from different Er sites.

The EL intensity has also been measured at RT as a function of the current density. These data are reported in Fig. 3 for the Er + O doped sample both under forward (closed circles) and under reverse bias (open circles). In both cases the EL intensity increases linearly with current density in the whole investigated range and no saturation is observed. This demonstrates that only a fraction of the optically active Er^{3+} sites are excited.

Further insight on the mechanisms behind this process can be gained by measuring the EL intensity as a function of temperature. In Fig. 4 the EL intensity vs the reciprocal temperature for the O and F co-doped samples is reported. Data are shown under forward (closed circles) and reverse (open circles) bias for a constant current density of 2.5 A/cm^2 through the device. For comparison the photoluminescence (PL) intensities measured on similar samples by pumping the unbiased devices with the 514.5 nm line of an Ar$^+$ ion laser are also reported (triangles). Several interesting features can be noticed. First of all the temperature dependence of the PL intensity and of the forward-bias-EL intensity appears interestingly similar. In both cases (and for both Er + O and Er + F samples) the luminescence decreases by about a factor of 30–50 on going from 100 K to 300 K. This decrease is much smaller than that observed in Er-doped Czochralski Si samples (without any additional impurity co-doping) in which a decrease in the luminescence intensity by almost 3 orders of magnitude was observed between 100 K and 300 K [4,5]. Hence impurity co-doping has dramatically reduced the temperature quenching. This quenching is further reduced under reverse bias pumping. In this case (and for both O and F co-doping) the EL intensity decreases only by a factor of 4 on going from 100 to 300 K, thus allowing a strong EL peak to be visible even at RT. In particular, in the Er + F diode, the reverse-bias EL is equal to its forward bias counterpart at 100 K but, due to its reduced thermal quenching, at RT the EL is 5 times higher under reverse bias than under forward bias.

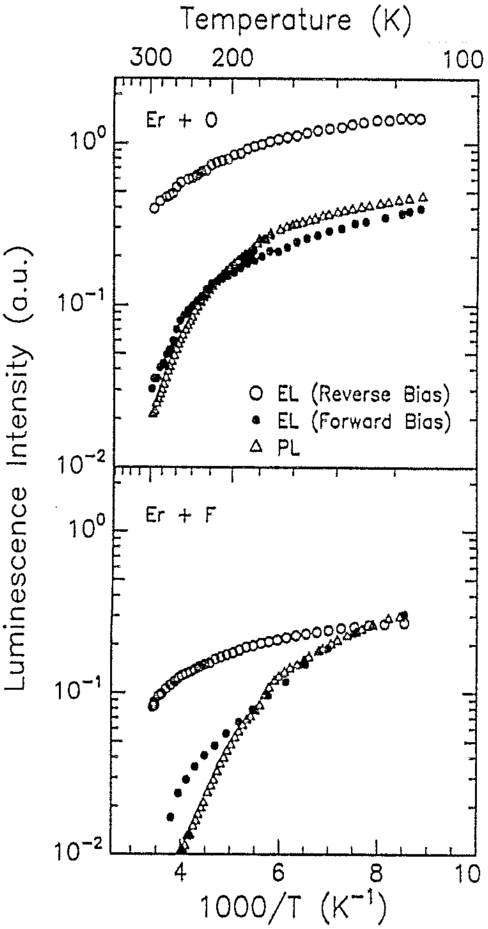

Fig. 4. Temperature dependence of the EL intensity under both forward (●) and reverse bias (○) conditions. Data are taken for both the Er + O doped diode (upper part) and for the Er + F doped diode (lower part). For comparison the temperature dependence of the PL intensity (△) in the two cases is also reported and is normalized to the forward bias EL value at 110 K.

These data give us a hint on the understanding of the Er luminescence in Si. In particular, the similarity in the temperature dependence between PL and forward-bias-EL suggests that similar excitation mechanisms are operative in these two cases. It has been demonstrated that PL in Er-doped Si is due to an indirect pumping process in which the laser light produces e–h pairs and subsequently an e–h mediated recombination process excites the Er^{3+} ion. This process has been suggested to be the recombination of an exciton bound to the neutral donor level of the Er ion [7] or, alternatively, an Auger recombination of a hole in the valence band with an electron in a trap level (Er-related) with the energy released to the inner 4f Er^{3+} shell [9]. In both cases an Er-related level in the Si bandgap plays a major role in the pumping process. In fact efficient photoluminescence can only arise from those Er^{3+} ions introducing deep levels in the band gap at which e–h recombination, with an efficient energy transfer to the rare-earth ion, can occur. We speculate that impurity codoping, which is known to modify the Er chemical surrounding, can also modify the properties of Er related deep levels facilitating the pumping process and thus enhancing luminescence. In view of the similarities observed above (Fig. 4) we assume that this scenario is true also for forward-bias EL.

A different picture emerges when reverse-bias EL is analyzed. The reduced thermal quenching reported in Fig. 4 suggests that a different excitation mechanism might be operative. Due to the large doping concentration on the two sides of the junction, our light emitting diode under reverse bias has a very small depletion layer (~ 40 nm) in which an intense electric field is present (~ 1.5×10^6 V/cm at −5 V). Under these conditions the carriers produced by band-to-band tunneling can be accelerated by the electric field and produce impact excitation of the Er^{3+} ions from the $^4I_{15/2}$ to the $^4I_{13/2}$ level. The energy required for this process is ~ 0.8 eV. An estimate of the mean energy $\langle \epsilon \rangle$ of the fast electrons in the space charge region can be done taking into account that these electrons lose energy mainly by optical phonon collisions [12,13].

Under this assumption

$$\langle \epsilon \rangle = \frac{(eE\lambda)^2}{3E_R},$$

where λ is the mean free path of carriers, E the electric field and E_R the optical phonon energy. Taking [13] $\lambda = 75 \times 10^{-8}$ cm and $E_R = 0.063$ eV this gives $\langle \epsilon \rangle =$ 0.8 eV for an electric field of 5×10^5 V/cm. Hence, also at very low reverse voltages, all the electrons crossing the device have enough energy to excite the Er ions. This explains why the EL intensity depends linearly on current (Fig. 3) and the fact that no threshold is observed.

It should be noticed that this pumping process is particularly efficient. In fact, the only Er ions that can be excited are those present in the space charge region, i.e. $3 \times 10^{13}/\text{cm}^2$ at most assuming that all the incorporated Er ions can be pumped by this mechanism. Nevertheless the EL signal is intense. By a comparison of our EL signal at a current density of 2.5 A/cm^2 with the PL intensity of Er in SiO_2 (for which the cross section for the direct pumping is known [11]), we can estimate the number of excited Er atoms. This resulted to be $3 \times 10^{11}/\text{cm}^2$, i.e. almost 1% of the excitable sites (in the space charge region). The rate equation for pumping through impact excitation will be

$$\frac{dN_{Er}^*}{dt} = \sigma J(N_{Er} - N_{Er}^*) - \frac{N_{Er}^*}{\tau},$$

N_{Er}^* being the number of excited sites, N_{Er} the total concentration of excitable sites, σ the cross section for impact excitation, J the density of hot carriers through the device and τ the lifetime of the excited state through both radiative and non-radiative routes.

In steady state, and assuming $1/\tau \gg \sigma J$:

$$N_{Er}^* = \frac{\sigma J}{\sigma J + \frac{1}{\tau}} N_{Er} \approx \sigma J N_{Er} \tau.$$

Since N_{Er}^* has been estimated above, N_{Er} is known and assuming ~ 20 μs for τ, we can estimate a lower bound of 3.2×10^{-17} cm^2 for the cross section σ for impact excitation of the $^4I_{13/2}$ level.

4. Conclusions

In conclusion we have shown that light emitting silicon diodes operating at room temperature can be fabricated by Er and O (or F) co-implantations. These diodes emit light at 1.54 μm under both forward bias and reverse bias conditions in the breakdown regime. The temperature dependence of the forward-bias EL is identical to that of photoluminescence suggesting that similar excitation mechanisms, mediated by an electron–hole recombination process, are operative. In contrast, under reverse bias, a weak temperature dependence is observed. We suggest that, in this case, pumping occurs through the impact excitation of the Er^{3+}.

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