Room-temperature electroluminescence from Er-doped crystalline Si

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We have obtained room-temperature electroluminescence (EL) at ~1.54 μm from Er and O co-doped crystalline p-n Si diodes fabricated by ion implantation, under both forward and reverse bias conditions. Under forward bias, the EL intensity decreases by a factor of ~15 on going from 110 to 300 K, where a weak peak is still visible. In contrast, we report the first sharp luminescence peak obtained under reverse bias conditions in the breakdown regime. In this case the EL intensity decreases only by a factor of 4 on going from 110 to 300 K and the room-temperature yield is more than one order of magnitude higher than under forward bias. The data suggest that Er excitation occurs through electron-hole mediated processes under forward bias and through impact excitation under reverse bias.

Recently, an intense effort has been dedicated to the achievement of efficient room-temperature light emission from Si.[1] Among the several different approaches, the introduction of Er impurities in Si has been recognized as one of the most promising. In fact, Er^{3+} ions exhibit a sharp luminescence at ~1.54 μm as a result of an internal atomic $4f$-shell transition which, in the Si host matrix, can be excited both optically and electrically.[2,3]

The Si:Er system has been the subject of extensive investigations[4–14] which has greatly increased our present knowledge of the behavior of Er in Si. For instance, the crucial role played by impurities in modifying the Er chemical surrounding[4] and in enhancing the luminescence[5,6] has been recognized. Moreover, the luminescence mechanisms involving carrier-mediated processes have been investigated and resonant Auger recombination[7] as well as exciton recombination[8] have been proposed as possible mechanisms. It has been recognized that the major problem towards possible applications is the strong temperature quenching of the luminescence intensity, which is seen to decrease by ~3 orders of magnitude on going from 77 to 300 K.[6,9] Electroluminescence (EL) of Er-doped Si p-n diodes was first reported in 1985 by Ennen *et al.*[3] at a temperature of 77 K and temperature quenching severely hampered its observation at 300 K. Only very recently a report was made for room-temperature EL.[10]

We have shown[11] that the temperature quenching of the photoluminescence (PL) is strongly reduced in samples produced by solid phase epitaxy of an amorphous Si surface layer co-doped with Er and O. In this letter we will show that room-temperature (RT) electroluminescence at ~1.54 μm can be obtained in this sample, provided that Er and O co-doping is performed in a suitable diode structure. Furthermore, we will report the first intense and sharp luminescence peak obtained at RT under reverse bias conditions in the breakdown regime of an Er-doped crystalline Si diode. These data will be presented and speculations on the possible mechanisms will be provided.

We have realized Er-doped p^+-n^+ Si diodes by implanting different species into an epitaxial n-type (7 Ω cm) layer grown on top of (100) oriented heavily n-type doped (10^{-2} Ω cm) Si wafer. The p^+ region of the device was formed by 40-keV B implantation at a dose of $5\times10^{15}/\text{cm}^2$, while part of the n^+ region was produced by 2 MeV P to a dose of $5\times10^{15}/\text{cm}^2$. Six different Er implants in the energy range 0.5–5 MeV were then used to introduce an almost constant Er concentration of $1\times10^{19}/\text{cm}^3$ in the middle between the n^+ and p^+ regions. Several different O implants in the energy range 0.15–1.4 MeV were subsequently performed to produce an almost constant O concentration of $1\times10^{20}/\text{cm}^3$ in the Er-doped region. Since Er in presence of O shows a donor behavior,[12,13] this region is of n^+ type and, together with the P-doped region, forms the n^+ side of the junction.

All of these implants were performed at room temperature and produced a continuous amorphous layer extending from the surface to a depth of 2.3 μm. After implantation, samples were annealed at 620 °C for 3 h under N_2 flux in order to induce the epitaxial recrystallization of the amorphous layer.[8,14] A further thermal treatment at 900 °C for 30 min under N_2 flux with a partial pressure of O_2 was performed in order to electrically activate the implanted dopants and also to grow a thin oxide layer (50 nm) to passivate the Si surface. This recipe has been shown to produce a good quality Er and O co-doped Si single crystal.[8] Finally, aluminum patterns were photolithographically defined on the samples allowing some open area for the exit of the light.

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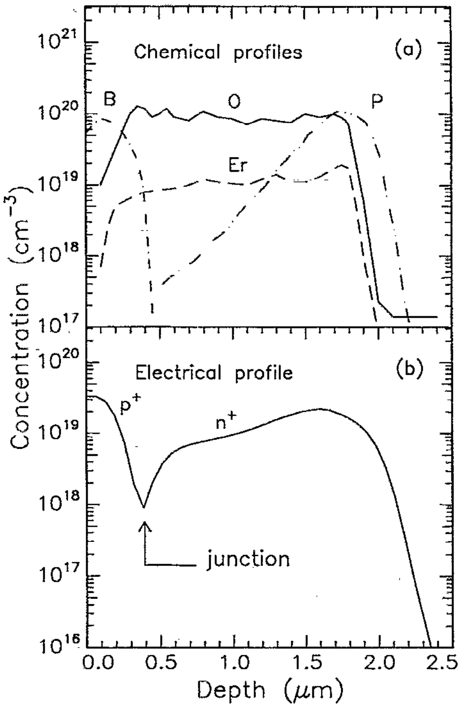

FIG. 1. SIMS profiles of the various implanted impurities introduced in the diode structure (a). The profiles have been taken after subsequent thermal treatments at 620 °C—3 h and 900 °C—30 min. The electrical profile of the diode structure as obtained by spreading resistance analysis is also reported (b). The junction depth is indicated.

The resulting devices have an area of 0.25 cm^2, half of which is covered by aluminum.

The secondary ion mass spectroscopy (SIMS) profiles of the various implanted impurities are shown in Fig. 1(a). The electrical profile, as obtained by spreading resistance measurements, is reported in Fig. 1(b). All the different features of the device are clearly shown. In particular the electrical profile shows that p^+-n^+ junction is located at a depth of $\sim$400 nm.

Current-voltage (I-V) characteristics of this diode are shown in Fig. 2. Data are taken at both 110 and 300 K. An analysis of the forward I-V curves demonstrates that the device is in the recombination regime at both temperatures and in the whole investigated voltage range. The reverse I-V characteristics of the diode are identical at the two temperatures and show a breakdown voltage of ~ -5 V. Taking into account the high dopant concentration on the two sides of the junction, this breakdown is likely to be due to the Zener effect.

EL measurements on this diode were performed by biasing it with a square pulse at 55 Hz and varying the current through the device both under forward and reverse bias conditions. The luminescence signal from a $\sim$1 mm in diameter circular area was collected by a lens, analyzed with a monochromator and detected by a liquid-nitrogen-cooled Ge detector. Spectra were recorded using a lock-in amplifier with the voltage pulse as a reference.

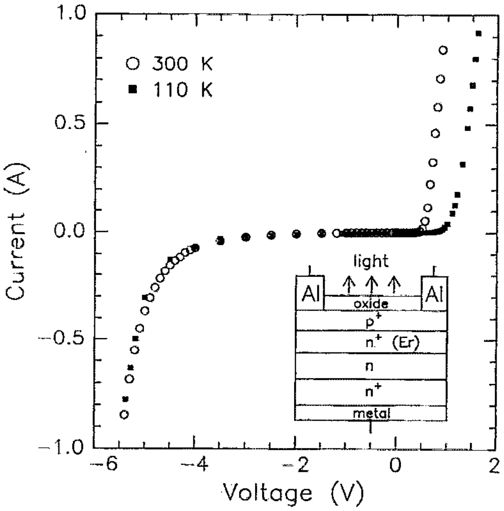

FIG. 2. I-V characteristics of the diode taken at 110 and 300 K. The diode area was 0.25 cm^2. A schematic picture of the device is also reported.

Figure 3 shows the room-temperature EL spectra taken at current densities of 2.5 A/cm^2 in different conditions. Under forward bias conditions (+1.4 V) a weak signal is observed (●) but the spectrum clearly shows the typical structured shape of the luminescence of Er-doped Si. In contrast, under reverse bias in the breakdown regime (−5.3 V), a sharp and intense peak at $\sim$1.54 μm is observed (○). This peak is 16 times higher than its forward current counterpart at the same current density and we estimate that the total collected power is of $\sim$2 μW. This is the first clear room-temperature EL from Er-doped crystalline Si obtained in the breakdown regime. Note that no degradation of the diodes was ever observed, even after several hours of operation at maximum power.

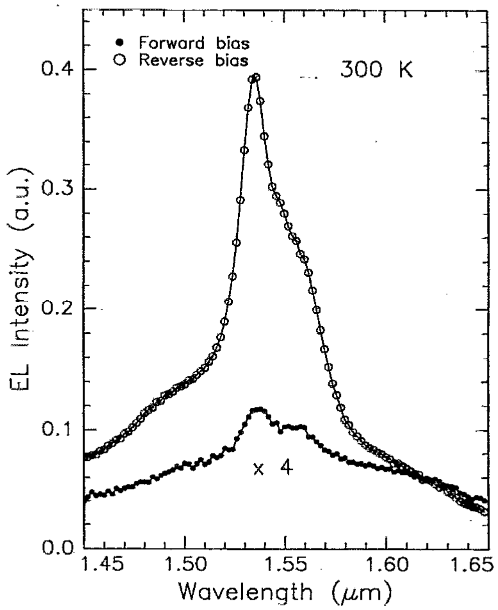

FIG. 3. Room-temperature electroluminescence spectra under forward bias (●) and reverse bias conditions (○). The spectra are taken at a constant current density of 2.5 A/cm^2 (corresponding to a total current of 600 mA). The spectrum under forward bias conditions is multiplied by a factor of 4.

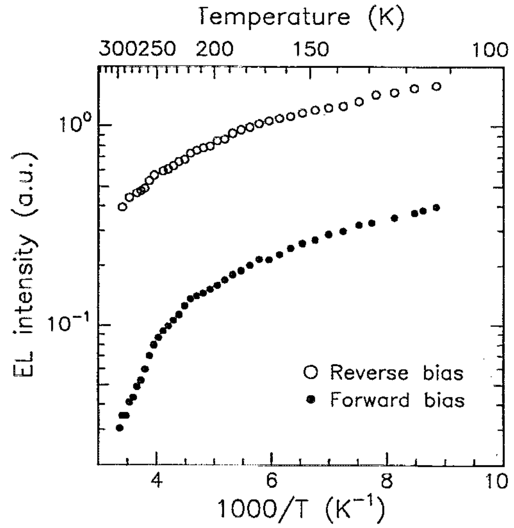

FIG. 4. Temperature dependence of the EL intensity under both forward and reverse bias. Data are taken at a constant current density of 2.5 A/cm^2.

We have measured the EL yield as a function of the current density in the range 0.1–2.5 A/cm^2. Under both forward and reverse bias, the EL intensity increases linearly with the current density passing through the device, indicating that not all of the excitable Er atoms are excited.

The temperature dependence of the EL intensity at a constant current density of 2.5 A/cm^2 is shown in Fig. 4 and is significantly dependent on the biasing conditions. Under forward bias the yield decreases by about a factor of 15 on going from 110 to 300 K. This temperature dependence is very similar to that of the PL intensity in Er and O co-doped samples.[11] This indicates that, in analogy with PL experiments, the Er is excited through an electron-hole mediated recombination process. The temperature quenching under reverse bias is very different, as the yield decreases only by a factor of 4 on going from 110 to 300 K. This difference is quite intriguing and suggests that a different mechanism is responsible for Er excitation under reverse bias.

We have estimated that the electric field in the space-charge region is $\sim 1.8\times 10^6$ V/cm under reverse bias in the breakdown regime. Since the electron mean-free path in our samples is estimated to be ~5 nm, the energy of hot carriers accelerated by the electric field is ~0.9 eV. This energy is sufficient to excite the Er^{3+} ions from the $^4I_{15/2}$ to the $^4I_{13/2}$ level. Hence, impact excitation might be the pumping mechanism under reverse bias. Impact excitation is known to be one of the pumping mechanisms of Er in InP[15] and the present results are the first indication that it might be operative also in Si.

In conclusion, we have shown room-temperature electroluminescence from an Er-doped Si *p-n* diode, co-doped with oxygen. EL is observed both in forward and in reverse bias conditions, with the largest intensity obtained under reverse bias (−5.3 V) in the breakdown regime. From the temperature dependence of the EL intensity it is concluded that under forward bias Er is excited through an energy transfer process involving recombination. In contrast, under reverse bias, Er is likely to be excited by impact excitation.

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