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OPTICALLY ACTIVE Si:Er LAYERS GROWN BY THE SUBLIMATION MBE METHOD

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We report the first application of sublimation molecular beam epitaxy to grow uniformly and selectively doped Si:Er layers with Er concentration up to 5×10^{18} cm^{-3}. The Hall concentration of electrons is about 10% of total Er contents. The mobility is 300–400 cm^2 V^{-1} s^{-1} at 300 K. All samples exhibit photoluminescence at 1.537 μm up to 100–140 K.

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1. Introduction

Erbium in silicon has attracted considerable interest because of its potential to give high-efficiency sharp luminescence at 1.54 μm, the optimum wavelength for optical telecommunication systems. The development of Er-based devices depends on the ability to incorporate optically active Er^{3+} ions efficiently into the host material. A high volume density, at least about 10^{18} cm^{-3} of Er ions [1], is required to fabricate technologically useful devices and to obtain sufficient luminescence intensity. One particularly attractive way to incorporate Er ions into Si is via molecular beam epitaxy (MBE) at low temperature (500–600°C) [2, 3].

In this article we report for the first time on the application of sublimation MBE (SMBE) to grow Si layers with a high concentration of erbium and the investigation of their properties. This method allows to grow uniformly doped monocrystalline layers of Si, as well as structures with a specified doping profile, with the concentration of the main electrically active impurities as Sb, P, Al, As in the range 2×10^{13}–4×10^{20} cm^{-3} [4, 5]. Moreover, the impurity segregation in SMBE can be avoided without special contrivances [5]. In the SMBE method the role of the Si source and the doping source is played by the plate of Si, doped by the desired element, here in particular Er. The doping level in the SMBE layers is determined by the source impurity concentration, the growth velocity and the substrate temperature [4, 5].

2. Experiment

The Si:Er layers were grown in a vacuum of 2×10^{-7} mbar on Si(100) p-type substrates ($\rho \approx 10$ Ω cm). Si plates doped with Er up to $\approx 10^{21}$ cm^{-3} were used as a source for both the Si and Er vapors. The Si source and the substrate were heated by electrical current. The substrate temperature was 400–700°C. After the growth process, the structures (except for the selectively doped structures) were annealed in a vacuum chamber at 900°C for 30 min. The thickness of the Si:Er layers varied from 0.2 to 3 μm.

The Er and O profiles and the Si crystal quality were characterized with secondary ion mass spectrometry (SIMS) and Rutherford backscattering spectroscopy (RBS). The profiles of free carriers at room temperature were determined by the Hall and C–V measurements. The electrically active defects in the layers were detected using deep level transient spectroscopy (DLTS) at 50–350 K. The photoluminescence (PL) spectra were measured in the range of 4.2–300 K using BOMEM DA3.36 and DA8 Fourier spectrometers with Ar^+ ($\lambda = 514.5$ nm) and Kr^+ ($\lambda = 647$ nm) lasers as excitation sources.

3. Results and discussion

Figure 1 shows the SIMS profiles of Er and O in the SMBE film grown at 600°C. The Er and O concentrations are distributed rather homogeneously with values of 5×10^{18} and 4×10^{19} cm^{-3}, respectively. This fact confirms that both Er and O segregation on a growth surface is insignificant. Decreasing the substrate temperature down to 400°C does not cause any significant changes in the Er and O profiles. On the other hand, enhancing the growth temperature up to 700°C leads to Er segregation, seen by an inhomogeneous Er profile. Here the oxygen can be incorporated in the samples from the residual gas of vacuum chamber or from Si:Er source.

RBS measurements were performed for Si:Er structures grown at 600°C. The profiling results (random conditions) are close to those shown in Fig. 1. The channeling has been performed for the $\langle 100 \rangle$ axis and the $\{110\}$ and $\{100\}$ planes. The minimum channeling yield in the Si part of the spectra (axial case) is $\chi_{min} = 5\%$, in the planar case 27% and 35% respectively. This demonstrates the high crystalline quality of the samples. The Er yields show the same angular dependence as Si yields in all measured directions, which seems to indicate that

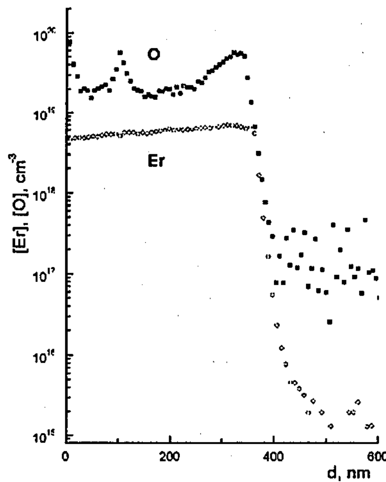

Fig. 1. Er and O profiles (SIMS data) for Er-doped film grown on Si(100) at 600°C. The depth is counted from the outer sample surface.

erbium is incorporated both at substitutional and tetrahedral interstitial (T_d symmetry) lattice sites. Selective etching of Si:Er layers ($d \approx 3$ μm) does not reveal any packing defects and additional dislocations as compared to the substrate.

A selectively doped Si:Er structure comprising three Er doped layers was grown taking advantage of the fact that only insignificant Er segregation occurs at the growth surface. The layer growth temperatures were 580, 440, and 580°C, the expected thicknesses — 2, 1, and 40 nm respectively (from the outer surface to the substrate). The Er-doped layers were separated by undoped layers (≈ 1, 0.5, and 0.5 μm in thickness) grown from a high resistivity n-Si source. The $C-V$ profile (Fig. 2) shows three sharp peaks corresponding to the selectively doped layers. The carrier concentration in the narrower layers was evaluated by integrating $C(V)$ results using the nominal layer thicknesses giving 1.4×10^{18} and 2.4×10^{18} cm^{-3}. These values are close to those for uniformly doped reference layers grown at 600 and 400°C. The selective etching revealed neither packing defects nor additional dislocations with respect to the substrate.

All the grown layers show n-type conductivity, independent of the substrate properties and the heat treatment conditions (with 900°C annealing or without it). Hall measurements gave concentrations of 4×10^{17} and 2.5×10^{17} cm^{-3} and mobilities of 340 and 370 cm^2 V^{-1} s^{-1} for the uniformly doped layers grown at 400 and 600°C, respectively. The electrical activity of Er in these layers is about 10%, as in implanted structures [6]. SIMS and $C-V$ profiles were close to each other for all grown structures, thus confirming the correlation of donor activity with Er atoms.

We report here also the first DLTS data for SMBE Si:Er layers (and for MBE layers also). The levels detected (with activation enthalpies of 0.17, 0.26, 0.32, and 0.44 eV relative to the bottom of the conduction band) are close to those seen in

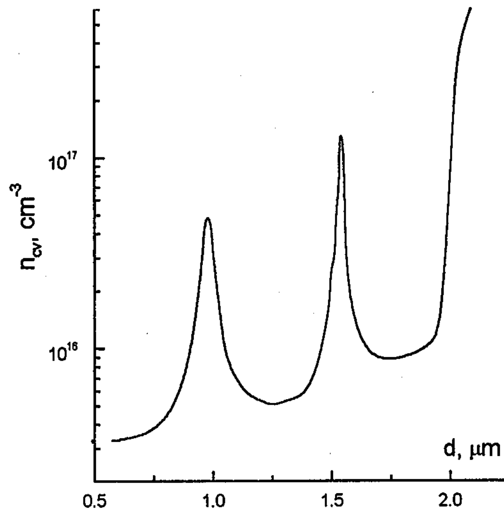

Fig. 2. $C-V$ profile for a selectively doped Si structure. The depth is counted from the outer sample surface.

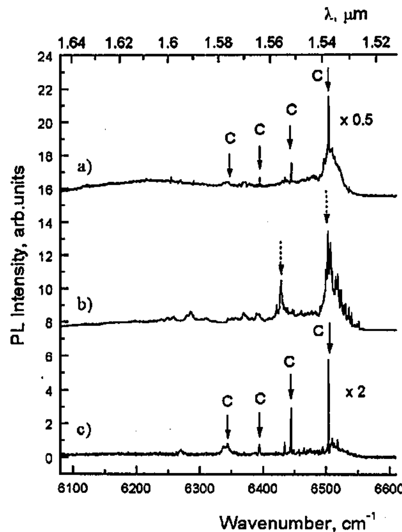

Fig. 3. PL spectra of SMBE grown Si:Er. The curves *a* and *b* were obtained for the samples grown at 600 and 400°C respectively, *c* — for selectively doped structure. The PL signal has been scaled by a factor of 2 (*c*) and 0.5 (*a*). The spectral resolution is 0.5 cm^{-1}. The sample temperature is 4.2 K.

Er-implanted Si. The intensive lines with energies more than 0.48 eV, typical of implanted layers [7, 8], are absent in our spectra. As the PL signal is sufficiently intense in both SMBE and implanted structures we suppose that these levels are not responsible for exciting the PL in Si:Er structures. We suppose that they correspond to complicated defects arising from the Er implantation process.

Figure 3 shows PL spectra of the uniformly doped samples grown at 600°C (*a*) and 400°C (*b*) and the selectively doped structure (*c*), respectively. All spectra exhibit a sharp peak at 1.537 μm. For the layer grown at 600°C an optically active Er center is observed with its main lines due to the optical transitions $^4I_{13/2} \rightarrow {}^4I_{15/2}$ at 6504.1, 6444.8, 6394.1, and 6344.6 cm^{-1} (labeled "C" in Fig. 3a). Taking into account the number of lines [7], their positions and RBS channeling data, this seems to indicate Er^{3+} ion to be in the site with tetrahedral symmetry.

The PL spectrum of the sample grown at 400°C is more complicated. It includes two intense lines at 6502.9 and 6429.2 cm^{-1} and a series of extremely narrow lines at 6506.8$\div$6551.4 cm^{-1}. This indicates the presence of some optically active Er centers with lower symmetry, possibly complicated Er–O complexes [7].

The spectrum shown in Fig. 3c is close to that in Fig. 3a. The other Er-related PL series and Si defect-related lines were not observed.

The temperature dependencies of PL intensity for structures uniformly doped at 400 and 600°C show the PL temperature quenching of above 90 and 140 K, respectively. For the 600°C structure the temperature dependence of PL shows two activation energies of $\approx$ 13 and 60 meV. The first value is relevant for the temperature range of 30–80 K and is close to results for implanted [7, 9] and MBE [10] layers. The latter value characterizes the temperature regime of $T > 80$ K and is smaller as compared to [7] (80–100 meV).

4. Conclusion

The uniformly and selectively doped Si:Er structures are grown at 400–600°C by SMBE for the first time with a high concentration of Er and O (up to 5×10^{18} and 4×10^{19} cm^{-3} respectively). All structures exhibit photoluminescence close to 1.54 μm up to 100–140 K. Optically active Er centers with their main lines at 6504.1, 6444.8, 6394.1, and 6344.6 cm^{-1} were observed in the PL spectra of most grown layers. PL and RBS data seem to suggest that this center is related to Er^{3+} ion in the site with tetrahedral symmetry.

According to Hall effect measurements the electron concentration is $\approx$ 10% of the total Er concentration and the mobility — 300–400 cm^2 V^{-1} s^{-1} at room temperature. DLTS data show defects with an ionization energy $E_i \leq 0.48$ eV.

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