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Electrically active centers in light emitting Si : Er/Si structures grown by the sublimation MBE method

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Abstract

The electrically active centers in light-emitting Si : Er/Si structures grown by an original sublimation MBE (SMBE) method are investigated using admittance spectroscopy and deep level transient spectroscopy. It is shown that free carrier concentration in investigated structures is determined by shallow donors with ionization energies varying from 0.016 to 0.045 eV. The essential difference between deep level defects observed in SMBE Si : Er/Si structures and in Si : Er/Si structures produced by ion implantation is revealed. The causes of observed distinctions between electrical and optical properties of SMBE structures as well as distinctions between SMBE and ion implanted Si : Er/Si structures are discussed.

Keywords: Sublimation MBE; Si : Er/Si structures; Electrically active centers

1. Introduction

Silicon doped with erbium has been attracting attention as promising material for producing effective light emitters radiating in the range of the maximal transparency of silica glass optical fibers ($\lambda \approx 1.5\,\mu m$). Recently, there were demonstrated Si : Er/Si structures with rather high photo- (PL) and electroluminescence (EL) including PL and EL at room temperature produced with an original sublimation MBE method (SMBE)—MBE variant, in which molecular flows of Si and Er are formed using sublimation of Si crystal initially doped with Er and other necessary dopants [1–4].

We report here on electrically active centers detected in light-emitting SMBE Si : Er/Si structures and their transformation caused by post-growth heat treatment. The observed distinctions between electrical and optical properties of SMBE structures as well as distinctions between SMBE and ion implanted Si : Er/Si structures are discussed.

2. Experimental

We investigated uniformly doped Si : Er/Si structures grown on n-Si and p-Si substrates with (1 0 0) orientation and specific resistivity of 20, 10 and 0.005 Ω cm. The sublimating sources were plates cut from Si : Er ingots with Er and O contents up to 5×10^{20} and $1 \times 10^{19}\,cm^{-3}$, respectively. The growth temperature varied from 400 K up to 600 K and the thickness of the layers from 0.2 μm up to 3 μm. The post-growth annealing of the structures was carried out at $T = 900\,K$ in H_2 atmosphere.

Energy levels in the band gap of Si were investigated using DLTS and admittance spectroscopy at the temperature range from 10 to 350 K. Admittance measurements were conducted in a frequency range

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from 100 Hz to 1 MHz. The conductance and capacitance components of the current passing through the sample under investigation were taken by synchronous detection of the signal. DLTS measurements were performed at 400 kHz using double boxcar integrating technique [5]. Combining DLTS and admittance measurements has allowed us to identify both shallow and deep levels.

Schottky contacts were prepared by thermal evaporation of Pd onto the sample surface at 6×10^{-6} torr. The ohmic contact was prepared by rubbing an In–Ga alloy onto the back surface of the sample or evaporating a Schottky contact of large size (Si : Er layers on high-resistance p-Si substrates).

3. Results and discussion

All investigated SMBE Si : Er layers were n-type, irrespective of the growth temperature and annealing conditions. The free carrier concentration as it was shown by admittance measurements was 10^{16}–$10^{18}\,cm^{-3}$ at $T = 300\,K$ and was determined by shallow centers with ionization energies of 0.016–0.045 eV. The background contamination introduced by the apparatus during SMBE process was near $2 \times 10^{13}\,cm^{-3}$ [4,6]. Note that this estimation does not take into account the residual impurities containing in Si : Er sources.

The admittance spectra $C(T)$ and $G(T)$ shown in Fig. 1 are taken at zero bias and test signal frequency of 80.6 kHz. Note that the peak in $G(T)$ and the step in $C(T)$ are caused by freezing out of the carriers in the neutral region of Schottky diode and the corresponding enhancement of its resistance which is inserted in turn with the capacitance of the space charge region. The change of test frequency results in a shift of the observed admittance spectra along the temperature axis. At the bottom of Fig. 1 an Arrhenius plot is given. The ionization energy obtained from the slope of the Arrhenius plot has the value of 0.016 eV. During data processing, we have considered the temperature dependence of the effective density of states in the conduction band $N_c(T) \sim T^{3/2}$ neglecting the temperature dependence of the carrier mobility.

The type of conductivity fixed by these shallow centers and their forming conditions encourage to relate them to thermal donors—oxygen-defect complexes formed in Si crystals under heat treatment. The role of Er in forming these centers is not clear up to now. Probably, the Er atoms because of their greater size in comparison with Si atoms introduce appreciable distortions to the Si lattice and accelerate thermal donor formation [7]. There are distinctions between the ionization energies of shallow levels observed in SMBE layers grown from various Si : Er sources. Probably, they are caused by distinctions in impurity contents of different Si : Er sources, especially it concerns such impurities as C, N, O which may be involved in the observed shallow defects.

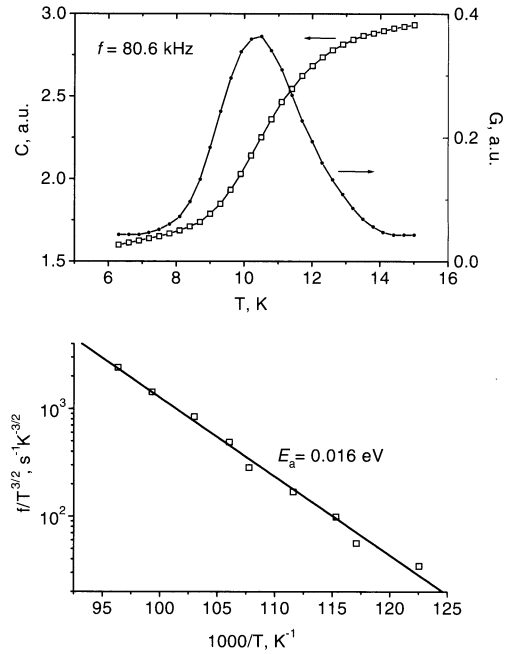

Fig. 1. Admittance spectra of shallow impurities in SMBE Si : Er/Si structure. The spectra are taken at frequency $f = 8 \times 10^2$ to 8×10^4 Hz and $U_{bias} = 0$.

A deep defect concentration is rather low in investigated SMBE structures. As-grown layers show usually a relative trap density $N_T/(N_D - N_A) < 0.1$. The ionization energies are in the range of 0.15–0.45 eV (Fig. 2). Their concentrations do not depend on the type of the used substrate and depend strongly on the growth and annealing conditions. Trap concentrations are maximal in layers grown at lower temperature ($T_{growth} < 500\,K$) and decrease with increase of T_{growth}. The distinctive feature of these defects is that they are completely annealed by an additional post-growth heat treatment in particular by an annealing at 900 K during 30 min in H_2 atmosphere. In contrast, the post-growth annealing at the same conditions causes the transformation of light emitting centers but does not destroy the PL as a whole (Fig. 3). The PL connected with Er^{3+} passes through the minimum at $T_{annealing} = 750\,K$ and then strongly increases up to $T_{annealing} = 900\,K$. It concludes that above mentioned deep electrically active centers do not participate in the energy transfer to Er^{3+} ions. Most likely, they are related to growth defects.

This is the most essential difference between the electrically active centers observed in SMBE and implanted Si : Er/Si layers. In implanted layers, one detects deep levels in the range of 0.1–0.3 eV including

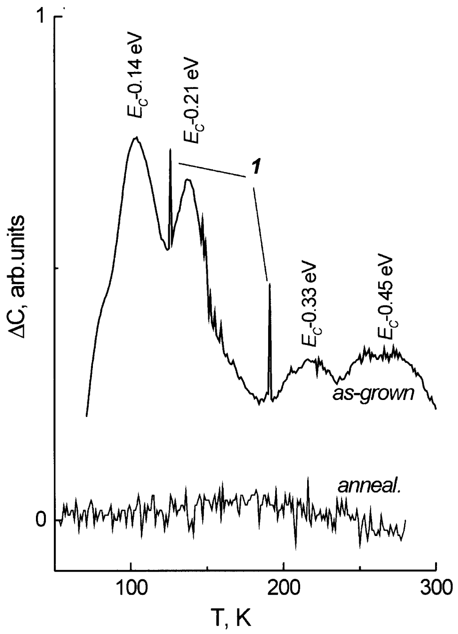

Fig. 2. DLTS spectra of a SMBE Si : Er/Si structure as-grown and after annealing ($T_{growth} = 430\,K$, annealing conditions: 900 K, 30 min., H_2). The DLTS spectra are taken at $\tau_{window} = 0.6\,ms$, $U_{bias} = -2\,V$. 1—calibration pulses, the amplitude of calibration pulse is $\Delta C = 10^{-3} \times C$, where C is the diode capacitance at the temperature of calibration.

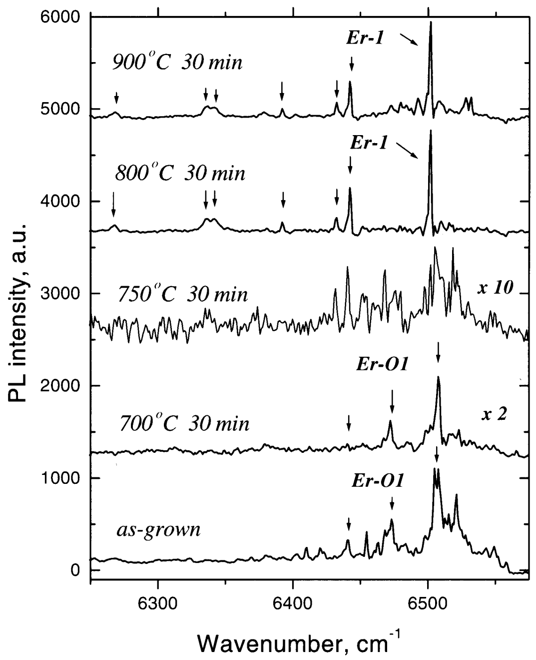

Fig. 3. PL spectra of uniformly doped Si : Er/Si structure depending on $T_{annealing}$. $T_{growth} = 430\,K$ [3].

the level $E_c - 0.15\,eV$ which according to nowadays concepts is responsible for the transfer of energy to Er^{3+} [8]. In SMBE layers despite of the intensive PL connected with erbium we could not detect deep levels in the same energy range. We have summarized below some results obtained from capacitance and PL experiments with the Si : Er/Si structure uniformly doped with Er in SMBE process and revealing the intensive PL at liquid helium temperature. Its parameters are as follows: the substrate is Si : B, $20\,\Omega\,cm$; T_{growth} is 500°C; the Si : Er layer width is $\sim 2.7\,\mu m$; the structure was annealed at 800°C (30 min, H_2). Free carrier concentration slightly increases from 3×10^{16} on the surface to $2 \times 10^{17}\,cm^{-3}$ in the interior of the Si : Er layer; Er and O concentrations determined from SIMS measurements are 1×10^{18} and $3 \times 10^{19}\,cm^{-3}$ accordingly. The concentration of optically active centers related to erbium N_{Er}^{opt} estimated from PL measurements is $2 \times 10^{16}\,cm^{-3}$ [9]. On the other hand, the concentration of electrically active centers with the ionization energy in the range of 0.1–0.3 eV that could participate in the transfer of energy to Er^{3+} ions (via the mechanism of an exciton capture [8]) $N_{Er}^{el} < 1 \times 10^{13}\,cm^{-3}$ (DLTS data). So, huge distinction between N_{Er}^{opt} and N_{Er}^{el} revealed in this experiment indicates that most probably the additional channels of energy transfer to Er^{3+} ions take place in SMBE Si : Er/Si structures in comparison with ion implanted ones.

4. Conclusions

In this contribution, we have presented the investigation of electrically active centers in Si : Er/Si structures produced by an original SMBE method. We have shown that the free carrier concentration is determined by shallow donors with ionization energy of 0.016–0.045 eV. The most unexpected result is that we have not yet detected any electrically active centers responsible for the energy transfer to Er^{3+} ions in investigated SMBE structures. So, we assume the presence of complementary channels in SMBE structures for the energy transfer to Er^{3+} ions in comparison with ion implanted structures.

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