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The influence of rare earth elements on the optical properties of silicon epitaxial films

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Abstract.
The results of growing erbium-doped silicon epitaxial layers using two different growth modes are presented: conventional molecular beam epitaxy (MBE) and solid-phase epitaxy (SPE). It is shown that an erbium-doped silicon layer deposited by PFE on a cold substrate and subsequently annealed exhibits more intense photoluminescence at a wavelength of 1.54 μm than layers grown by MBE.
Keywords: photoluminescence, epitaxial film, deformation, intensity, mechanical stress.

Introduction. The growing number of studies on erbium-doped silicon is associated with the possibility of using this material to create silicon optoelectronic devices at a wavelength of 1.54 μm [1]. One of the conditions for the successful implementation of silicon device structures is achieving a high content of optically active centers associated with erbium. When doping silicon with erbium using ion implantation, high-energy ions (0.5–5 MeV) are used. This leads to the formation of defects that remain partially even after prolonged annealing and lead to the precipitation of rare earth impurities [2]. During ion implantation, as in other doping methods, optically inactive silicide compounds are formed as a result of the interaction between erbium and silicon atoms. It has been established that in order to suppress the formation of erbium precipitates and erbium silicides, it is necessary to carry out the doping process at low temperatures and to dope silicon layers with oxygen to form optically active centers containing Er3+ ions [3]. Using molecular beam epitaxy (MBE) with silicon and erbium evaporation, it is possible to grow layers with a total erbium concentration of up to 10 22cm−3 [4]. However, the intensity of photoluminescence in layers with an erbium concentration greater than 10 18cm−3 begins to weaken, which is probably due to the formation of defects in the crystal structure [4,5]. Another method for growing heavily doped silicon layers is solid-phase epitaxy (SPE). The growth process involves two stages: deposition of the layer at low temperatures, when impurity segregation is kinetically suppressed, and subsequent annealing of the amorphous silicon film [6]. The aim of this work is to investigate the possibility of growing heavily erbium-doped silicon layers using the TPE method, which exhibit photoluminescence at a wavelength of 1.54 μm.

Experimental method

Erbium-doped silicon layers were grown in an ultra-high vacuum MLE system using the device shown in Fig. 1[7]. Si evaporation was carried out from a sublimation source in the form of a rectangular bar heated by an electric current, and Er evaporation was also carried out from a sublimation source cut from metal foil. The substrate was a rectangular silicon plate cut along the (100) or (111) plane from KDB-12 single-crystal silicon. Like the sources, it was heated by passing a current through it. After annealing the substrate at T=1250°C for 10 min, silicon layers were grown either by the MLE method at a substrate temperature of 500°C or by the TFE method on a heated substrate followed by in situ annealing. The PL spectra of the structures were measured at a temperature of 77 K using a BOMEM DA3 Fourier spectrometer with a resolution of 1 cm−1 when pumped with Ar+ laser radiation (with a wavelength λ=514.5 nm) with a power of 80 mW from the epitaxial layer side. The structure of the layers was studied by electron microscopy. The photoluminescence spectrum of this structure, measured at liquid nitrogen temperature, is shown in Fig. 1. Wide The band with a maximum at 6500 cm−1 is characteristic of the Er^{3+} ion in Si : Er/Si structures obtained by sublimation MLE with a metallic erbium source and containing a higher concentration of oxygen and carbon (compared to the erbium content).

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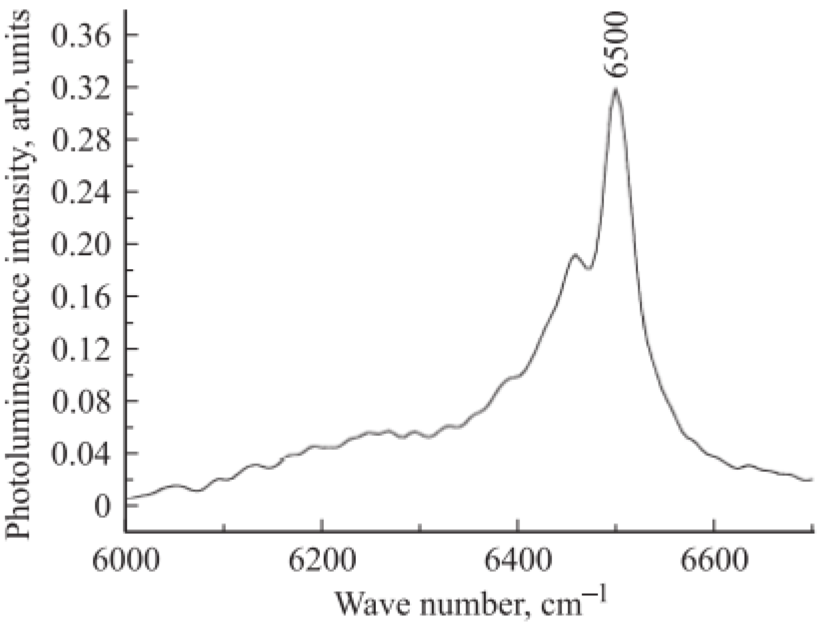

Fig. 1. FL spectrum of a structure grown by MLE. The spectrum was recorded at T = 77 K and argon laser pump power P = 80 mW.

The photoluminescence spectrum of erbium in an epitaxial silicon layer grown by TFE is shown in Fig. 2. The spectrum contains an intense series of narrow luminescence lines corresponding to the $^4I1_{3/2}\rightarrow^4 I1_{5/2}$ transition in the 4f shell of the Er^{3+} ion in a known isolated emission center with cubic symmetry [8]. Such a spectrum is typically characteristic of erbium in single-crystal silicon with a low oxygen content (compared to the erbium concentration). At the same time, the integral luminescence intensity of the Er^{3+} ion in the structure obtained in the TFE mode is twice that in the structure grown in the MLE process. According to existing ideas about the mechanism of TFE of amorphous silicon layers deposited in a vacuum on a single-crystal substrate, annealing causes the epitaxial crystallization front to move from the single-crystal/amorphous film interface to the surface of the layer [9]. If, at an annealing temperature of 600°C, the crystallization of amorphous silicon on a single-crystal substrate occurs due to the epitaxial ordering of atoms of the amorphous phase near the single-crystal/amorphous film interface, then at 800°C C, there is additional nucleation and growth of randomly oriented crystallites in the volume of amorphous silicon.

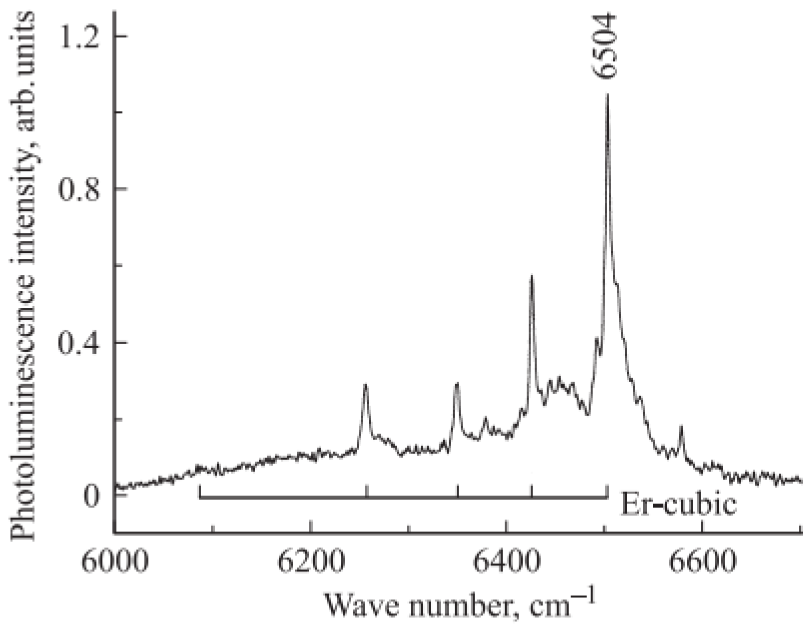

Fig. 2. FL spectrum of a structure grown in TFE mode. The FL recording conditions are the same as for the spectrum in Fig. 1.

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The rate of epitaxial crystallization at 800°C is 2.2–10 nm/min. Such a high crystallization rate leads to the fact that at the end of annealing, part of the surface is occupied by a single-crystal phase, and part by a polycrystalline phase. The effect of oxygen on slowing down the crystallization rate was reported in [10]. However, when oxygen is introduced in our experiments at the moments when the growth process is suspended, a layer of adsorbed gas of insignificant thickness is likely to form, which may only be partially captured by the growing layer. As a result, the total amount of oxygen introduced into the layer is insignificant. This, apparently, causes the observed changes in the photoluminescence spectrum of Er^{3+} ions in silicon layers grown by the TFE method. Thus, the solid-phase epitaxy method allows the formation of a heavily erbium-doped layer on a silicon film sawed in an ultra-high vacuum, which exhibits more intense photoluminescence than a layer grown by molecular beam epitaxy.

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