Optical memory effect in Si:Er

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In two-color experiments utilizing a Nd:YAG (532 nm) laser pulse and a free-electron laser (7 - 17 μm), we revealed that Si:Er exhibits afterglow and optical memory effects. Both features, observed for T<50 K, are manifestations of properties of Si matrix, conveniently revealed by emission at 1.54 μm by the optical dopant. Detailed investigations of the free electron laser (FEL)-induced Er emission show that this excitation mechanism is governed by ionization of a single type of charge carrier. This implies that hole and electron capture events can be separated in time.

Introduction

Present-day Si electronic technology based on crystalline silicon (*c*-Si) is very quickly approaching fundamental limitations, which are difficult to overcome by engineering. The problems being faced are of a basic scientific nature and are unlikely to be solved by minor adjustments. Further increases of integration scale of Si chips are limited by heat dissipation and the restrictions imposed on the oxide thickness by leakage currents. Therefore, a fundamentally different approach has to be found. This can be offered by Si-based photonics [1]. Rare earth doping of semiconductors, is one of the promising approaches to obtain efficient light emission. In particular, one of the most studied systems is Si:Er (Si-doped with erbium) because the intra 4f-electron shell transition of this ion falls in the range of minimum loses of silica-based optical fibers used in telecommunications.

Unfortunately emission from Si:Er exhibits strong thermal quenching. Such an effect indicates important participation of shallow states in energy transfer mechanisms in Si:Er. The state-of-the-art silicon technology offers a total control over shallow states. Therefore, it should be possible to eliminate, or even positively engineer thermal effects, once their role in the emission process of *c*-Si:Er is understood. Investigation of thermal effects is, however, experimentally difficult due to their indeterminate activation. Two-color spectroscopy in the mid infrared region with a free electron laser (FEL) provides a new convenient tool to investigate these thermal effects. These experiments have revealed new information concerning optically doped semiconductor matrices [2]. In particular, they confirmed the involvement of shallow traps in energy transfer processes between the Er^{3+} ion and the Si host [3] and identified the relevant shallow centers by utilizing their ionization cross-sections [4] Also the MIR-activated mechanism of Er emission has been recently observed [5]. Ionization due to MIR pulses accelerates slow energy transfers, which would otherwise easily escape detection. In this way, the prominent role of non-equilibrium traps in the energy storage process could be deduced. In *c*-Si:Er, hole trapping at shallow impurities (acceptor or acceptor-like) gives rise to an afterglow effect and to the MIR-induced Er PL enhancement [6].

Experimental set-up

The idea of the two-color experiment is presented in the inset of Fig. 1. A Si:Er sample placed in a cryostat at a T ~ 5 K, is exposed to two-correlated laser beams operating in different wavelength ranges. The pump beam, Nd:YAG laser, provides band-to-band excitation leading to emission at 1.54 μm photoluminescence (PL). A secondary pulse from the FEL, with an adjustable time delay, is fired at a mid infrared (MIR) wavelength of choice (7- 17 μm). The change of Er PL emission (intensity, dynamics) can be followed as a function of the MIR wavelength and power, as well as the delay time between the both laser pulses. Intense radiation from the FEL allows optical spectroscopy of thermal effects. In combination with the band-to-band excitation it offers a possibility to investigate thermal effects in the ground and excited states of Er ions, and to probe non-equilibrium and metastable states. Data presented here is shown for a particular sample prepared from Czochralski-grown *p*-type (boron doped) silicon. Er ions were implanted with energy of 300 keV. The concentration of Er in the implanted layer was around $5x10^{17}$ cm^{-3}. The sample was co-implanted with oxygen ions with energy of 40 keV. Oxygen co-doping is known to increase intensity of Er PL and to reduce its thermal quenching. The implantation was followed by 900 ^{0}C annealing during 30 minutes.

Results and discussion

Fig. 1shows Er PL at 1.54 μm taken with Ge detector (response time ~ 75 μs). An intense FEL pulse (λ = 10 μm) is fired after 80 ms delay time in respect the band-to-band Nd:YAG pulse. As a consequence extra Er emission is seen.

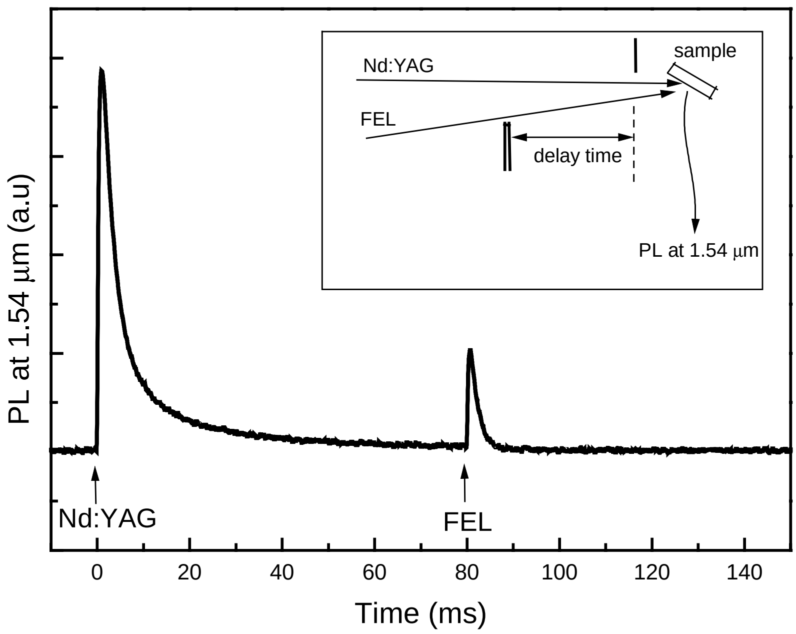

Fig. 1. Er PL kinetics at 1.54 μm under Nd:YAG excitation at t=0 with FEL fired with a delay of 80 ms. In the inset the experimental set-up is shown, see text for explanation.

Recent investigations have shown that the afterglow [5] is related to the MIR-induced Er PL emission. The explanation of this effect is as follows: Following the band-to-band pump pulse, free electrons and holes are generated. These are captured by trapping and recombination centers available in the material. In this way, excitation of Er ions takes place via particular trapping centers (Er-related donor level) followed by their emission, which forms the initial PL peak for t = 0 in Fig. 1. However, there is competition for electron and hole capture between Er-related level and other carrier traps. We note here, that Si substrate is *p*-type (boron doped). Therefore, an additional excitation of the Er ions will take place upon release of holes initially captured and temporarily "stored" at those additional traps. This can be accomplished thermally, giving rise to a slowly decaying "afterglow" component in the PL signal [5,6]. Alternatively, a FEL laser pulse, at 80 ms delay can induce carrier released optically from the traps. Since the MIR-induced emission of the Er PL is controlled by the optical ionization of traps previously populated by the pump pulse, it represents an optical "memory effect" similar to that observed in GaN [7]. Application of the MIR ("reading") pulse generates Er emission only if it follows shortly after the pump ("writing") pulse, as schematically depicted in Fig. 2.

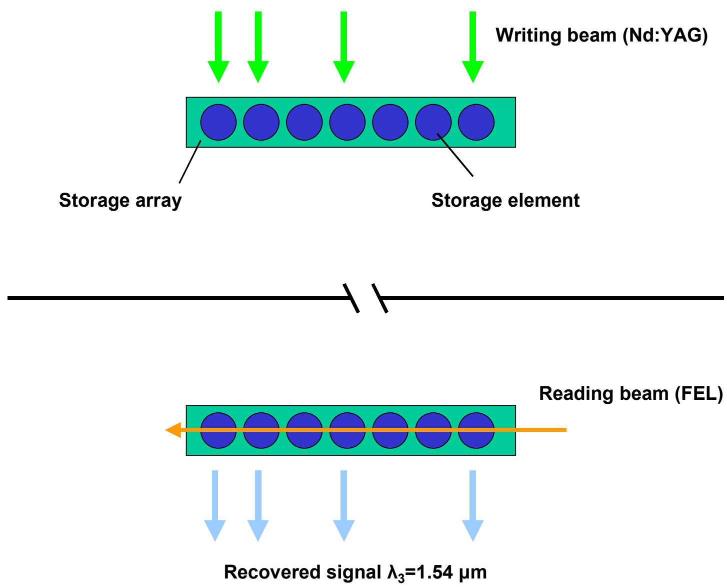

Fig. 2. Schematic illustration of "all-silicon" optically memory element based on the described optical memory effect.

The fact that the "archival time" of the optical memory effect exceeds 100 ms, gives us an indication that excitons cannot be responsible in this case for Er excitation. Reported lifetime of free excitons in silicon is on the order of ~ 1 ms while bound excitons lifetime is not longer than ~ (100-200) µs (for isoelectronic centers). Consequently, two-color spectroscopy reveals a previously unrecognized excitation path of Er^{3+}. Future research needs to show whether this sequential excitation path could be utilized for improving the thermal stability of emission from Si:Er.

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