Terahertz Raman Laser Based on Silicon Doped by Phosphorus

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***Abstract*— Raman-type stimulated emission at frequencies between 5.0 and 5.2 THz as well as between 6.1 and 6.4 THz has been realized in silicon crystals doped by phosphorus donors. The Raman laser operates at around 5 K under optical excitation by a pulsed, frequency-tunable infrared free electron laser. The Stokes shift of 3.16 THz is equal to the difference between the energies of the phosphorus ground state, 1s(A_1), and the 1s(E) split off state.**

I. Introduction And Background

Lasing in silicon is notoriously difficult to achieve. The first silicon laser that has been realized operated on intracenter transitions in phosphorous doped silicon[1]. Later on lasing on intracenter transitions of other group-V impurities has been demonstrated. All of these lasers operate in the range between 1.5 THz and 7 THz[2]. More recently Raman-type lasers based on conversion of infrared light in the lattice of silicon have been demonstrated[3]. A THz Raman-type all-intracenter silicon laser doped by antimony (Si:Sb) has been reported in 2006[4]. In this Raman laser scattering of pump photons occurs on two lower donor states, resonantly coupled via the TA *g*-phonon. This interaction enhances the scattering efficiency and Raman gain. Here, we report on the realization of a THz Raman laser made from silicon doped by phosphorus[5].

II. Experimental setup

The silicon crystals used in the experiments were grown by the float zone technique in [111] direction. Phosphorus donors were incorporated by simultaneous doping from the melt. The silicon crystals had a phosphorus concentration of N_D= (2–3) 10^{15} cm^{-3}. The samples were optically polished rectangular parallelepipeds with dimensions of about 7x7x5 mm^3. The largest facet was orthogonal to the growth axis. All facets were chemically-optically polished parallel to each other with an accuracy of 1 arcmin. This forms a low-loss resonator for modes on total internal reflection. We used the Dutch free electron laser FELIX for pumping the silicon lasers. FELIX generated 6 μs long macropulses at a 5 Hz repetition rate in the range from 27 to 40 μm. Each macropulse consisted of a train of micro-pulses with a duration of about 6 - 8 ps separated by 1 ns. The pump radiation irradiated the ⟨111⟩ facet of the silicon sample. The FEL power incident on the sample was controlled by a calibrated step-attenuator and measured by a Joule-meter. The silicon samples were mounted in a dedicated sample holder which was immersed into a liquid helium (lHe) transport vessel providing a temperature of 4.2 K. The pump radiation was guided to the sample by a stainless steel tube. A thin polyethylene (PE) film on top of the pump tube served as a window for the pump radiation. The laser emission was directed out of the transport vessel onto a Ge:Ga detector. Any remaining radiation from the FEL was blocked by a 1 mm-thick z-cut crystalline quartz filter and an additional filter made from high density PE. The emission spectra were measured with a Fourier transform spectrometer.

III. Results

Intracenter pumping of Si:P below 10^{24} photons $cm^{-2}s^{-1}$ results in stimulated emission occurring each time when the pump photon energy corresponds to a dipole allowed optical transition originating from the ground state, 1s(A_1). At maximum pump power (about 10^{25} photons $cm^{-2}s^{-1}$) additional emission lines appear even when the pump frequency does not correspond to an intracenter transition but is close to the two low energy donor transitions 1s(A_1)→$2p_0$ (34.11 meV) and $1s(A_1)\rightarrow 2p_\pm$ (39.19 meV) (Fig. 1). Its photon energy, $\hbar\omega_S$, varies with the pump photon energy, $\hbar\omega_{FEL}$, as $\hbar\omega_S = \hbar\omega_{FEL} - \Delta E$, where $\Delta E = 13.05 \pm 0.05$ meV is very close to the interstate energy gap between the phosphorus ground state and the split-off doublet 1*s*(*E*), which is 13.01 meV. Except for one line (one of the two lines which occur at pump energy of 34.1 meV, marked with I in Fig. 1) all other lines marked with roman numbers are due to stimulated, Stokes-shifted Raman emission. The stimulated emission corresponding to lines number II and III has an almost two order of magnitude larger laser threshold than those laser lines originating from resonant intracenter pumping transitions which is an indication of Raman emission. In addition, both lines are significantly offset from any intracenter pump transition. The lines marked with IV and V in Fig. 1 with a frequency close to the $2p_\pm \rightarrow$ 1s(E) transition have large laser thresholds as well. In addition, one of the lines (no. III) appears at a pump frequency, which is significantly offset from resonant excitation into the $2p_\pm$ state. Therefore, we assume that both lines are due to Raman emission.

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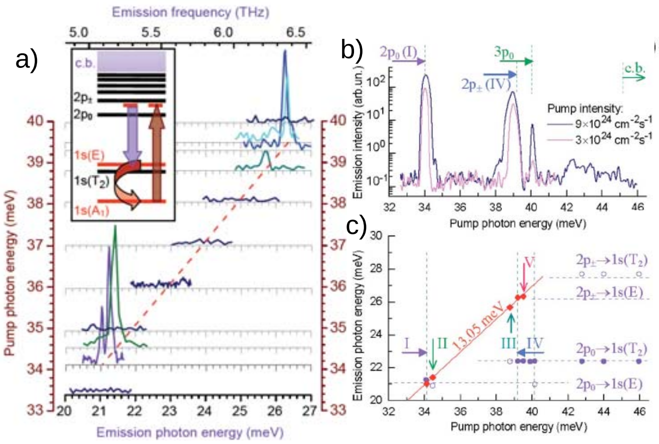

Fig. 1: Emission spectra of the Si:P Raman laser. The inset shows the scheme of Raman laser process (a). Dependences of the emission intensity (b) and emission photon energy (c) on the pump photon energy.

In the case of resonant pumping into the $2p_0$ state (marked by I in Fig. 1) the frequency difference to the intracenter $2p_0 \rightarrow 1s(E)$ transition is not significant. In this case the distinction between Raman and intracenter emission follows from an analysis of the temporal structure of the laser pulse and the emission spectrum as shown in Fig. 2. The pulse has two maxima at maximum pump power of 5×10^{25} photons cm^{-2} s^{-1} (0 dB attenuation). The relative intensity of the maxima is rather unstable from one pump pulse to the next indicating a competing character. When decreasing the pump power the first peak disappears and the pulse becomes stable. Spectral measurements performed with a time gate (shown by rectangles in Fig. 2) show that the front part of the emission pulse corresponds to one strong line at 21.00 meV. It does not correspond to an intracenter transition. This line (Fig. 2a) has a significantly (~15 dB) lower laser threshold and appears first after the pump pulse. The second part of the emission pulse appears with a ~0.5-1 μs delay. The spectrum corresponding to this part of the pulse consists of two lines. One is the line which is attributed to the first pulse peak which signal persists. The frequency of the other line corresponds to the $2p_0 \rightarrow 1s(T_2)$ transition (21.25 meV). The front peak of the emission pulse disappears at pump intensities below 10^{25} cm^{-2} s^{-1} (Fig. 2c) and so does the corresponding line in the emission spectrum. For these reasons we attribute the low frequency line to Raman emission while the high frequency line is due to the intracenter $2p_0 \rightarrow 1s(E)$ transition.

It is worth noting that the peak power of the Raman emission pulse was estimated to be a few mW at maximum pump power. There are other lines in the emission spectra (Fig. 1) whose frequency does not change with pump power. These lines can be attributed to the intracenter transitions $2p_\pm \rightarrow 1s(T_2)$ and $2p_0 \rightarrow 1s(T_2)$. The emission from the $2p_\pm \rightarrow 1s(T_2)$ transition is rather weak due to the competition with the $2p_0 \rightarrow 1s(T_2)$ which is more efficiently populated when pumping occurs into higher excited states or into the conduction band.

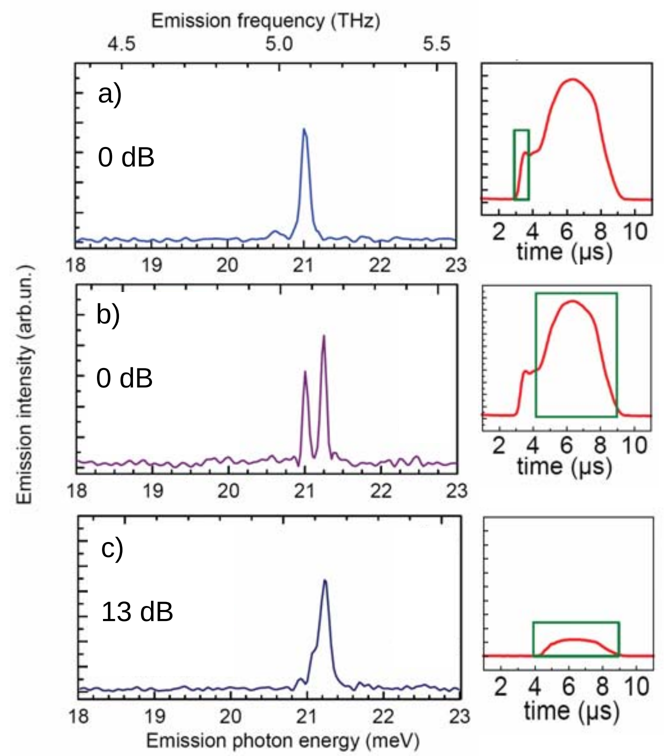

Fig. 2: Emission spectra (left) and corresponding emission pulses (right) recorded for the case of resonant pumping into the $2p_0$ state (line I in Fig. 2). The spectra are taken with different time gates shown by the rectangles in the insets. The labels in dB indicate the attenuation of the pump power; 0dB corresponds to 2×10^{25} photons$\times cm^{-2}\times s^{-1}$.

In contrast to the Si:Sb Raman laser Raman lasing in Si:P has been observed only in close vicinity to the $2p_0$ and $2p_\pm$ states, where the condition of the "incoming" Raman resonance is almost satisfied. We attribute this difference to the absence of the resonant coupling of the $1s(A_1)$ and 1s(E) states with the intervalley phonon as it occurs in Si:Sb Raman lasers.

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