Semiconductor lasers for mid- and far-infrared frequency ranges based on intracenter transitions

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State of art for terahertz (THz) emitters based on intracenter impurity transitions in bulk and heterostructure semiconductors is reviewed. The laser mechanism is based on the accumulation of optically or electrically pumped charge carriers on a particular long-living excited impurity state of the centers with binding energies in the range of 30-130 meV. Laser pulsed output has been obtained from bulk Si under optical pumping at liquid helium temperature. Some other bulk and heterostructure media have already demonstrated THz-range spontaneous emission.

Introduction.

The generation of *far-infrared* (or *terahertz*) stimulated emission is of great interest for basic and applied research. The physical processes dealing with the above mentioned frequency range include photoexcitation spectra of shallow impurities in semiconductors, cyclotron resonance and lattice vibration frequencies in solid states, energy gaps in low-dimensional semiconductor structures and in superconductors, as well as the rotational spectra of molecules. From an application point of view, the development of fundamental coherent and tunable far-infrared sources is of paramount importance in solid state spectroscopy, radio astronomy, active imaging as well as environmental monitoring. There is a lack of efficient, compact, solid-state sources for the wavelength range of 30-300 μm (1–10 THz). *Conventional semiconductor band-gap lasers* require sophisticated performance for far-infrared light generation (see, e.g. [1]).

It is difficult to reach the population inversion conditions for far-infrared in solid-state media. The reason of this is that fast (~10^{-11}-10^{-12} s, see e.g. [2]) *acoustic-phonon-assisted* and *Auger relaxation processes*, inherent for solids, equalize non-equilibrium carrier distributions on the THz-range-spaced states of the electron (sub-)bands. To overcome this fast carrier relaxation from an upper laser level one has to design a laser scheme, where the depletion of a lower electron state is faster than this relaxation. Additionally, a relatively fast population of the upper laser level is required in order to obtain the maximum of a gain, since lattice absorption and resonator losses can be very high for particular THz frequencies. One approach has been realized for *intersubband semiconductor lasers*. In intra-valence-band p-Ge bulk lasers an upper laser subband (lifetime is ~3×10^{-11} s) is populated by electric field heating of heavy holes (lower laser state subband) followed by a recombination via an optical phonon (process rates are ~10^{12} s^{-1}). The p-Ge lasers of different modifications cover a broad frequency range (1-4 THz) and can perform up to 100 % of the continuous emission frequency tunability [3]. However, big energy consumption as well as the low gain (~0.02 cm^{-1}) of the p-Ge laser restricts their practical use. Another approach, based on a resonant tunneling (the process speed is ~10^{12}-10^{13} s^{-1}) of the electrons through a system of the quantum-size confined layers in specially designed heterostructures has been realized for quantum cascade lasers recently. These lasers operate on optical transitions between the electron sub-bands (the lifetimes of the upper and lower levels are ~10^{-11}-10^{-12} s). They have demonstrated already their high quantum output (with a gain ~10-20 cm^{-1}) in the broad near- and middle-infrared emission range (4-25 μm) and continuous wave operation up to the room temperature. Recently, the first THz laser has been obtained from a GaAs/AlGaAs cascade laser [4].

Another principle of far-infrared active media is based on amplification on optical transitions between *localized states of impurity centers*. The main feature of these lasers is that the particular excited impurity states are ***long living*** (≥ 10^{-9} s). This difference with the intersubband lasers occurs because of suppression of the acoustic-phonon-assisted recombination between the widely spaced bound states due to the momentum conservation [5]. In bulk n-Si, the suppression of the acoustic-phonon-assisted relaxation from the $2p_0$ excited state makes it relatively long-living (lifetime is ~ 10^{-9} s). Accumulation of non-equilibrium charge carriers on the state results in the population inversion between the $2p_0$ and the lower lying *1s*-splitted excited states with the shorter lifetimes [6,7]. Transitions between *resonant* and *localized* boron centers in strained Si/SiGe heterostructure have been reported recently to be used for the THz lasing under electric field pumping at liquid helium temperature [8].

1. Silicon lasers based on the optical pumping of donors

The principles of population inversion and laser schemes for bulk Si under excitation of shallow donor centers have been reported in [5-7]. Deceleration of the cascade relaxation of the non-equilibrium carriers on the particular localized impurity state provides a relatively long-living excited state (at 4K), following the four-level laser schemes (Fig. 1).

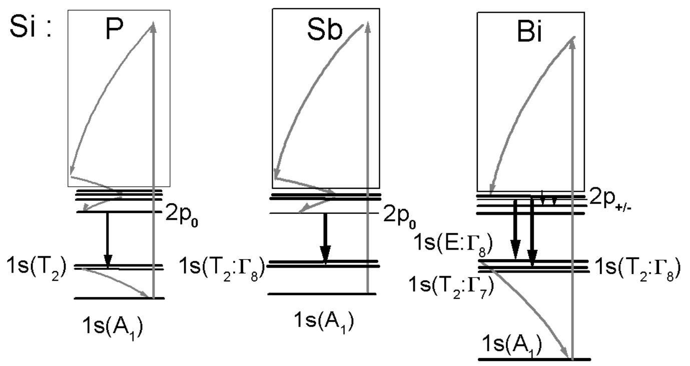

Fig. 1. Scheme of optical (vertical) and non-radiative transitions in Si lasers pumped by a CO_2 laser radiation. THz lasing (arrows down) occurs from the intracenter donor transitions. $2p_0$ is donor long-living state in Si:P and Si:Sb. Resonant depleting of the 2s and $2p_\pm$ state by an optical phonon forms the population inversion in Si:Bi.

Optical excitation of impurity centres by a laser with photon quantum energy of the same or higher than the binding energy of the dopant, leads to accumulation of excited carriers in this long-living state. These lasers require optical, CO_2 laser or another mid-infrared pump laser source [9], which can excite the electrons bound to donors above the upper laser level, $2p_0$ (Si:P [6], Si:Sb [10]) or the higher localized states (Si:Bi [7,11]). The laser's working temperatures are below 10 K. Their repetition rates (below 20 Hz) and the laser pulse durations (~70-300 ns on FWHM), are determined by the pump source. Different dopants and working conditions yield the different emission spectra for the Si lasers [7,12]. Si:Bi laser exhibits the most rich emission spectra, up to 6 different intracenter transitions, while all other Si lasers generate the only fixed line (Fig. 2).

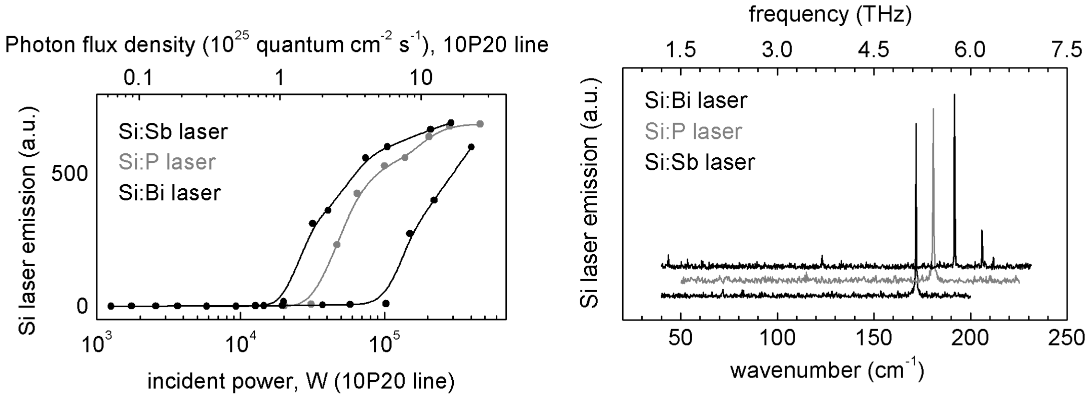

Fig. 2. Left graph: Dependences of the Si laser outputs on the pump power for the 10.6 μm pump line. Right graph: Si laser emission spectra for the 10.6 μm pump line (10P20).

Medium	The lowest threshold photon flux density and respective CO_2 pump laser line	Laser transition	Wavelength	Ref.s
Si:P	10^{24} photons×cm^{-2}×s^{-1}, 10.6 μm	$2p_0 \rightarrow 1s(T_2)$	55 μm	[6,7,12]
Si:Sb	10^{24} photons×cm^{-2}×s^{-1}, 10.6 μm	$2p_0 \rightarrow 1s(T_2{:}\Gamma_8)$	58.2 μm	[7,10]
Si:Bi	5×10^{25} photons×cm^{-2}×s^{-1}, 10.6 μm	$2p_\pm \rightarrow 1s(T_2{:}\Gamma_7)$	47.2 μm	[7]
	10^{25} photons×cm^{-2}×s^{-1}, 9.6 μm	$2p_\pm \rightarrow 1s(T_2{:}\Gamma_8)$	48.6 μm	[7,11, 12]
		$2p_\pm \rightarrow 1s(E)$	52.2 μm	
	5×10^{25} photons×cm^{-2}×s^{-1}, 10.6 μm	$4p_\pm \rightarrow 2s$	187 μm	[7]
		$4p_0 \rightarrow 2s$	229 μm	

2. Electric pumping of impurity centers in heterostructures

Another approach concerning the intracenter laser scheme for far- and mid-infrared can be realized in semiconductor heterostructures. The heterostructure design allows to spatially separate the pumping and the emitting channels. This gives a possibility to use both optical and electric pumping (Fig. 3), since the localized states in the barrier are not affected by the excitation mechanism.

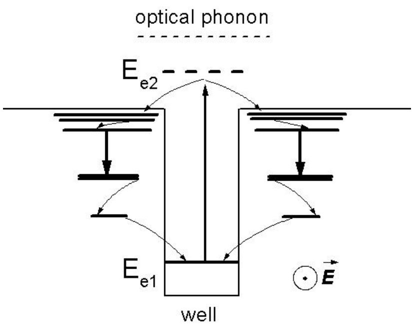

Fig. 3. Scheme of the electrically pumped far-infrared laser. The heterostructure is doped by shallow donors in the barrier layers. Electrons, which occupy the lower well subband E_{e1}, are accelerated by a lateral electric field ***E*** (straight arrow up) up to energies of the continuum, where they are captured onto the higher excited states of the impurity centers embedded in barriers. The far-infrared emission (straight arrows down) occurs on the optical intracenter transition in barriers. Curved arrows indicate acoustic-phonon-assisted relaxation of an electron.

The population inversion scheme is analogous to the laser schemes realized in bulk Si under optical pumping of shallow impurities. Although this principle is common for a set of semiconductors, Si-based heterostructures are of preferable interest. The intracenter laser action in bulk Si has already been demonstrated and investigated in detail. The first observation of intracenter spontaneous emission from the boron acceptor in Si/SiGe structure has been reported in [13].

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