6 Widely Tunable Far Infrared Hot Hole Semiconductor Lasers

ERIK BRÜNDERMANN[†]

Ruhr-Universität Bochum

Physical Chemistry II, NC 7/68

D-44780 Bochum, Germany

6.1 INTRODUCTION

The idea of hot hole lasers, and especially lasers using germanium material, has a long history which reaches back to the 1950s. Shockley [1] analyzed electron mobility data in germanium and its dependence on temperature and electric fields up to 40 kV/cm. He found that the significant scattering process of hot carriers is interaction with optical phonons, mainly optical phonon emission. This process has a threshold in carrier energy, the optical phonon energy which is 37 meV in germanium.

For high enough electric fields and at low temperature hot carriers accelerate without acoustical phonon interaction along the crystallographic direction in which the electric field is applied. These hot carriers reach the optical phonon energy and lose all their energy due to emission of optical phonons. They accelerate again, repeating this directional motion in momentum space. This motion is called streaming motion.

[†] E-mail:Erik.Bruendermann@ruhr-uni-bochum.de

The idea of using such a hot carrier, non-equilibrium distribution for amplification of long wavelength radiation was presented in 1958 by Krömer [2]. He proposed a so-called negative mass amplifier and generator (NEMAG) which utilizes warping of the constant energy surfaces and non-elastic optical phonon scattering. It was thought that such an oscillator using p-type germanium could be operated with an electric field of a few thousand V/cm along a $\langle 100 \rangle$ crystallographic axis.

Kurosawa and Maeda used Monte-Carlo simulations to investigate the properties of hole distributions in p-type germanium and in *perpendicular* electric and magnetic fields [3, 4]. They found a region in momentum space where carriers are accumulated, *i.e.*, carriers oscillate at the cyclotron resonance frequency with negligible scattering interaction. Within this work they proposed a laser mechanism which uses a transition from the accumulated region to the region where the carriers are not accumulated, *i.e.*, carriers frequently emit optical phonons and experience inelastic scattering in streaming motion.

In 1979 Andronov [5] proposed involving two bands in this mechanism, the valence bands of light and heavy holes, to form a population inversion. Finally, at the beginning of the 1980s several experiments demonstrated a population inversion in p-type germanium at 4.2 and 10 K [6, 7, 8, 9, 10]. Vorobjev *et al.* [10] found that a population inversion also exists at 80 K although less pronounced.

Traditionally, the laser process is divided into two mechanisms: the first involves a population inversion between the light and heavy hole bands (so-called intervalence-band or IVB lasers) and the second is based upon a population inversion between two light hole Landau levels (so-called light hole cyclotron resonance or LHCR lasers). This distinction is somewhat artificial because within the IVB laser a variety of simultaneous transitions occur which can be attributed to LHCR-type transitions. The LHCR laser is just a special case in which all other possible transitions have very low gain, e.g., by a special choice of crystallographic axes and acceptor concentration, to only maintain laser action between two light hole Landau levels. In general, the upper laser states are light hole states.

Strong stimulated emission was observed in 1984. Laser emission was attributed to transitions between the valence bands of light and heavy holes [11, 12] and between two light hole Landau levels [13]. The emission was stimulated in the wavelength range from 100 to 300 μm with an output power up to 10 W. The acceptor concentration of these germanium lasers ranged from 6×10^{12} cm^{-3} to 5×10^{14} cm^{-3}.

Another topic in the 1980s was the emission of germanium crystals in *parallel* electric and magnetic fields. The emitted wavelength lies between 1 and 5 mm. The emission is based on cyclotron resonance transitions of heavy holes with negative effective mass. This device comes close to the initial proposal by Krömer. A line width of less than 6 MHz was found for these lasers which allowed spectroscopic applications [14].

Various review articles [15, 16, 17] give a detailed overview of the field until 1987. A compilation of papers on germanium lasers and masers can be found in special issues [18, 19] published in 1991 and 1992.

Until 1995 all germanium lasers were doped with the hydrogenic acceptor gallium, except one which was doped with thallium [20]. These lasers operated with a low duty cycle of 10^{-5}. The laser performance was dramatically improved with the discovery of germanium laser material doped with non-hydrogenic acceptors, e.g., beryllium [21].

This material has led to strong laser emission up to duty cycles of 5% [22], repetition rates up to 45 kHz [23], and laser pulse lengths up to 32 μs [23]. Recently, non-thermal far-infrared emission was detected for continuous excitation [22].

Further technological improvements have led to a more convenient laser operation. Germanium lasers can be operated with small permanent magnets and in closed cycle refrigerators [24] at temperatures of up to 40 K [23] without the need for liquid helium.

6.1.1 Tunable germanium lasers

One key feature of the germanium laser is its large tuning range. The laser can be tuned by 60% in reference to the middle frequency of 2.5 THz or 83 cm^{-1}, respectively. Especially, lasers made from beryllium-doped germanium material can be tuned continuously over the spectral range from 30 to 140 cm^{-1} or 1 to 4 THz [25].

The peak of the gain spectrum, typically 10 cm^{-1} wide, is tuned by an external magnetic induction from 0.2 to 1.7 T. The rather wide gain spectrum can already be understood in a simple semi-classical model described in section 6.2.1. The underlying quantum mechanical mechanism of Landau level splitting is discussed in section 6.2.6.2 in detail. Within this gain spectrum a mechanical external resonator can be used to achieve single mode tunable far-infrared laser radiation. Germanium laser resonators will be discussed in section 6.5.1.

Above magnetic inductions of 1.7 T the gain spectrum narrows significantly because only a limited number of Landau level cyclotron resonance transitions, mainly light-to-light hole level transitions, are allowed. Then, the emission frequency is linear tunable with the magnetic induction with a ratio of approximately 20 $\mathrm{cm}^{-1}\mathrm{T}^{-1}$. The laser emits in a very narrow line (less than 0.1 cm^{-1}) even without an external mechanical resonator.

6.1.2 Motivation

The strong interest in a coherent, compact, powerful, tunable, continuous wave, solid state, and far-infrared laser is driven by a multitude of potential applications. Far-infrared molecular spectroscopy is an important tool to investigate chemical processes which occur in astronomical objects and in the atmosphere. Far-infrared lasers would be valuable as local oscillators in heterodyne receivers for the study of quantized rotational states of molecules and fine structure lines of atoms in atmospheric research [26] and in starforming regions [27]. However, far-infrared radiation is strongly absorbed by water molecules at sea level so that most observations of the latter kind need to take place on airborne and spaceborne platforms. The limited space, power, and time of flight require compact size, continuous wave operation, and low power consumption.

A far-infrared, compact, powerful, and tunable laser would also be very useful in laboratory based applications. Many materials have signatures in the far-infrared or terahertz frequency region including dielectrics [28], semiconductors [28], superconductors [29], liquids [30], and gases [31].

Interesting physical phenomena also exist in this spectral region: van-der-Waals bonding energies, e.g., in soft molecular crystals, molecular clusters, biomolecules and organic semiconductors; bonding energies of molecules bound to surfaces and dust particles; molecular formation in flames [32]; protein vibrational states [33], and modes in DNA, e.g., base roll and propeller twist modes [34]; acoustical and optical phonons; hole energy states; and cyclotron resonance frequencies in three and lower dimensional systems. The germanium laser is a powerful, tunable, and very compact source operating in the terahertz frequency range which will allow us to harvest this wealth of scientific information.

The germanium laser system also offers a wide range of very interesting physically and technologically challenging problems. The laser depends on a rather large number of parameters. These parameters are: impurity, acoustical and optical phonon scattering, band structure, band warping, crystal symmetry, crystallographic orientations, electric and magnetic fields, Landau level structure, Stark effect, the magnetically induced Hall effect which in turn depends on the device geometry and device dimensions, photon-hole interaction, and temperature.

The near equal strength of the electric and magnetic field can lead to new physics because most textbook theories treat cases in which only one of the two fields is weak. The application of uniaxial stress gives another adjustable parameter to influence the band structure and scattering processes, mainly impurity scattering.

Gas laser heterodyne spectrometers have been used on an airborne platform for astronomical observations [35]. Continuous wave emission of the local oscillator is desired to efficiently use the flight or mission time. A Schottky diode can be used as a mixer in such heterodyne receivers. The diode typically requires 1 mW/THz local oscillator power. Hot electron bolometers can lower this power demand by one or two orders of magnitude.

Gas laser heterodyne spectrometer have a frequency resolution of 1 MHz at terahertz frequencies. This resolution is necessary to analyze Doppler-shifted molecular emission which allows one to extract information on the dynamic processes in molecular clouds. This information is crucial to determine the precursors of star formation.

As will be shown in the following sections the germanium laser is indeed a very useful device which not only promises to deliver the high performance required in airborne applications but also high power and short pulses, attractive features in laboratory based research. Short, several tens of picoseconds (ps) long pulses can be generated by mode-locked germanium lasers.

6.1.3 Applications

There have been several examples of terahertz imaging using short ps-pulses emitted from non-linear crystals which show great promise for applications in diverse fields like production quality control and medical imaging. However, such sources cannot deliver the high spectral purity and sufficient power which is required for many spectroscopic applications in semiconductor physics and physical chemistry.

The germanium laser is on the verge of becoming a source for widespread spectroscopic applications due to a range of improvements like convenient laser operation in a closed cycle machine, tunable resonators, and improved duty cycle. However, there were already a few applications of the germanium lasers in spectroscopy: intra-cavity absorption measurements of quantum wells [36], spectroscopy of semiconductors [13, 20], and spectroscopy of H_2O [37].

6.2 HOT HOLE LASER MODEL

In this section the concept of the hot hole laser is introduced. Qualitative and some quantitative results can already be derived from a very simple semi-classical model. This model will build a bridge to a quantum mechanical model and more detailed articles in the literature. The theoretical background of such lasers will be discussed in the light of experimental investigations. Carrier transport in a bulk semiconductor, band structure, effects due to the applied external electric and magnetic fields, and scattering mechanisms will be addressed. A few comments on the optical gain and