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The evidence of the great interest that the Hungarian engineering community takes in the field of optical communication is that this is the third special issue of the Journal on Communications dealing with this topic in the past three years. The bases of this attention are the rapidly increasing Hungarian telecommunication network, the scientific and some economical successes achieved in research and development institutions. These facts motivated the organization of the first Hungarian Workshop on Semiconductor Lasers (Budapest, 13-14 June 1994). The topic of the Workshop was concentrated around the physics and technology of new type semiconductor lasers and laser applications, but oral and poster presentations were given on the topics of femtosecond optics, integrated optics, optical transmissions and measurements moreover curricular questions of training in optoelectronics. The seminar has been organized by the Department of Semiconductor Optics of the Research Institute for Technical Physics and by the Department of Electron Devices of the Technical University of Budapest. The participants came from the following institutions: ALCATEL SEL AG Research Centre Stuttgart, Philipps-University Marburg (Germany), University of Bath, University of Lancaster (UK), University of Szeged, and from several departments of the Technical University of Budapest.

The papers of this issue are based on the lectures given at the Workshop, selected so that we could inform the

reader on the most up-to-date trends in semiconductor laser technology.

One of these trends aims the extension the range of the operating wavelength and/or the increase output power so that semiconductor lasers would be applicable in the infrared spectroscopy or as pump sources for fibre lasers and amplifiers. The paper presented by W.M. Yee and K.A. Shore deals with the realization problems of far-infrared lasers operating at 10–60 μm . F. Koltay and others reported about a high power (120 mW) laser at 1.22 μm .

The other very far-reaching branch of research aims to find laser structures that are well integrable to the optical telecommunications systems and may act as tuneable light sources, optical wavelength converters, optical switches, amplifiers, pulse regenerators. D. Baums and others introduce a very versatile laser structure for the purposes mentioned above. The inherent nonlinear effect of semiconductor lasers, the four-wave mixing, seems to be advantageously applicable for the ultrafast optical information technologies. W. Elsässer gives an overview of the physics and applications of nonlinear interactions in semiconductor lasers and amplifiers, while W.M. Yee and K.A. Shore theoretically investigate the exploitation of nearly degenerate four-wave mixing in laser diodes to implement phase conjugate mirrors and optical repeaters.

The guest editor hopes that these papers will be found interesting and useful by the readers.

I. HABERMAJER



István Habermajer graduated in electrical engineering from the Technical University of Budapest in 1959. He received the "dr.techn." degree in 1964, and the Candidate of Technical Sciences degree in 1989. From 1959 to 1963, he worked at the Hungarian Television Company. Since then he has been at the Technical University of Budapest, and became an Associate Professor at the

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LASING THRESHOLD CALCULATIONS FOR MID- AND FAR-INFRARED INTERSUBBAND SEMICONDUCTOR LASERS

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We study theoretically the conditions for achieving lasing action at mid-infrared and far-infrared wavelengths based on intersubband transitions in semiconductor quantum well structures. A carrier transport model related to the achievement of intersubband population inversion is presented, which takes into account resonant tunnelling and intersubband absorption-emission processes. The incorporation of optical loss analysis into the carrier transport model provides estimates of the lasing threshold current density consistent with the optical losses in the laser devices. It is shown that reasonably low threshold current density in the range of 1–5 kA/cm² is achievable for room temperature lasing at emission wavelength of 60 μm. Significantly higher threshold current density of 40–50 kA/cm² is required for lasing at 10 μm wavelength.

1. INTRODUCTION

The development of room-temperature semiconductor lasers operating in the mid- to far-infrared wavelength range has been pursued by various workers for over twenty years. The effort required to overcome the difficulties in achieving such laser action is expected to be repaid by the wide range of applications envisaged for the devices. Compact low-cost tuneable mid/far-infrared lasers would find ready uses in remote sensing, pollution monitoring, medicine, dentistry and free space telecommunications. In recent years, following spectacular advances in semiconductor material growth techniques, attention has been focussed on the use of quantum well (QW) semiconductor structures for enhancing the performance of a variety of semiconductor optoelectronic devices including semiconductor lasers. Although the thrust of that work has been in respect of near-infrared laser sources for optical fibre communications systems, some effort has also been given to the utilization of low-dimensional structures for the achievement of lasing at longer wavelengths. The primary target of those investigations has been the exploitation of intersubband transitions in semiconductor QW's. The principal attraction of QW structures is that the quantised bound-state energy levels in the wells are essentially determined by the thickness and depth of the QW's. Crucially, the well thickness and depth can be finely controlled during the semiconductor growth process. In principle, therefore, a semiconductor QW structure can be fabricated with prescribed energy levels. The task that remains is to arrange that population inversion and hence lasing action takes place between the chosen energy levels which correspond to a desired operating wavelength. Here is the essence of

the challenge to the device designer. It is found that for operating wavelengths of order 60 μm and greater, structures may be relatively easily identified for the achievement of population inversion. However, at such wavelengths optical losses make it very difficult to sustain laser oscillation. On the other hand, at "shorter" wavelengths (between say 5 μm to 10 μm) optical losses become less daunting but it is relatively more difficult to achieve population inversion. In both cases the achievement of lasing action is more readily facilitated at lower temperatures.

The difficulties inherent in simultaneously meeting the challenges of achieving population inversion and overcoming optical losses have impeded the development of mid- and far-infrared semiconductor lasers. Consideration of the basic quantum mechanics of the transition process between quantum bound states by Henderson *et al.* [1] suggested that inter-bound-state laser action would not be possible. The core of that argument was that the ratio of the lifetimes of the upper and lower energy states was the opposite to that required for lasing. These findings prompted the authors to advance the case for the utilisation of above-well quasi-bound state transitions to achieve the required population inversion. On the other hand, a sustained effort by Capasso and co-workers has developed a detailed understanding of the requirements for achieving light emission and lasing action via intersubband transitions in coupled QW structures. Operation of electroluminescent diodes [2] was achieved at an emission wavelength of 5 μm at operating temperatures up to room temperature. More spectacularly, lasing action at an operating wavelength of 4.3 μm was demonstrated at temperatures up to about 125 °K [3].

The work of Capasso and co-workers has given new impetus to efforts directed at achieving long wavelength semiconductor lasers. From a fundamental viewpoint, it is seen that a new class of semiconductor lasers has been obtained which utilise only one kind of charge carrier. Such devices may be termed unipolar semiconductor lasers. In the present case electron intersubband transitions have been utilised but semiconductor lasers utilising transitions between hole intersubbands are also conceivable. The considerable efforts made by these workers to achieve this important milestone underlines the significance of their work. It is clear that careful design of the structure was complemented by extremely intricate and challenging semiconductor growth. The latter was required to obtain the

multiple coupled well structure which permits the operation of the 'quantum cascade' semiconductor laser.

The demonstration of the quantum cascade laser should, it is argued, be seen as providing an invaluable proof-of-concept demonstration of intersubband lasing. It is apparent, however, that much device development work is required to both raise the operating temperature of the intersubband lasers and to achieve lasing at longer wavelengths. The aim of the present paper is to quantify the challenges which need to be met to reach the goal of operating room-temperature mid- and far-infrared semiconductor lasers.

The report by West *et al.* [4] of the first observation of an extremely large dipole infrared transition between QW subbands has revived significant interest in the original proposal by Kazarinov and Suris [5] for the achievement of intersubband infrared emission in coupled QW structures and superlattices. Infrared photodetectors based on intersubband absorptions in QW structures have been extensively studied and successfully implemented recently for wavelengths in the 4–12 μm range [6]. Spontaneous intersubband radiative emission in GaAs-AlGaAs superlattices was first observed and reported by Helm *et al.* [7]. However, in order to obtain coherent infrared lasing from intersubband transitions, it is necessary to achieve a sufficiently high degree of intersubband population inversion at reasonably low pumping. This represents a major challenge because of the overwhelming contribution of nonradiative phonon emission which depopulates the upper lasing subband at a very fast rate. Many schemes have been proposed to achieve intersubband population inversion, most of which concentrate on current injection pumping [8]–[12], while a few approaches focus on optical pumping using a CO₂ laser source [13], [14].

In early studies on current injection pumped infrared semiconductor lasers based on intersubband transitions, sequential resonant tunnelling has been used to populate the excited state and depopulate the ground state of an electrically biased multiple QW structures. Although weak spontaneous emission has been observed using the sequential resonant tunnelling QW structure [7], intersubband population inversion has not been achieved. This is due to the fact that sequential resonant tunnelling from the ground state of one QW to the first excited state of the adjacent QW represents carrier transport in an essentially two-level system, and that population inversion cannot be achieved using just two states. On the other hand, while population inversion may be possible using sequential resonant tunnelling from the ground state to the second or higher excited state of an adjacent QW, the subsequent 'rain-down' of electrons to the first excited state and the ground state makes population inversion between these two states very difficult.

In order to facilitate the selective injection of electrons into the first excited state and the removal of electrons from the ground state of an emission QW, resonant tunnelling QW energy filters have been proposed and shown to lead to intersubband population inversion [9]–

[11]. These studies, however, assumed a simple relation between the intersubband population inversion and the injection current density, without taking into account the relevant physical mechanisms of resonant tunnelling and intersubband emission-absorption processes in the electron transport dynamics. The purpose of the present paper is to review a theoretical model which has been developed for the calculation of intersubband lasing conditions. The relevance of the model has been highlighted by the recent experimental activity on this topic and it is hoped that the present contribution will form a basis for future detailed device modelling of intersubband semiconductor lasers.

The main element of the model is a description of carrier transport in a generic coupled QW structure which has been outlined in an earlier publication [15]. That work was related to the achievement of intersubband population inversion in triple QW structures but the general formalism is applicable to, for example, the quantum cascade laser configuration. The second significant challenge in the design of long wavelength intersubband lasers is to meet the conditions necessary for achieving lasing action. The requirement here is to incorporate optical loss analysis which takes into account the semiconductor laser device configuration. Such a description was provided in a recent publication [16]. Here we show how the complete formulation provides estimates of lasing threshold current density consistent with the optical losses in the laser devices for emission wavelengths of 10 μm and 60 μm . In section 2, we present the transport model which describes the electron population dynamics in two prototype resonant tunnelling QW structures where account is taken of intersubband emission-absorption processes. The transparency current density is calculated in section 3 taking into account the dependence on electron transit time and intersubband relaxation time. In section 4, the issue of optical loss is addressed for different doping densities in the cladding layers. The solution of the four-level carrier rate equations from the transport model in conjunction with the balance of gain and optical loss yields the threshold current density. Finally, we summarize the results in section 5.

2. THEORETICAL MODEL

2.1. Resonant Tunnelling Quantum Well Structures

In this section, two prototype coupled QW structures are considered [15] for the achievement of intersubband population inversion. The two structures have intersubband energy separations of 124 meV (corresponding to an intersubband resonant wavelength $\lambda = 10 \mu\text{m}$) and 21 meV ($\lambda = 60 \mu\text{m}$), respectively. The schematic conduction band profiles of the two structures are shown in Figs. 1 (a) and 1(b), respectively. In order to facilitate the selective injection of electrons into the upper subband and the removal of electrons from the lower subband of the emission QW, resonant tunnelling QW energy filters are used [10], [11].