Towards Wannier-Stark THz superlattice laser

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Abstract. Basing on measurements, computer simulations and calculations of transport properties in GaAs-GaAlAs superlattices (SL) with narrow (weak) barriers we propose and elaborate scheme of the SL Wannier-Stark (W.-S.) THz lasers. The laser transitions (tunable by applied voltage) are between levels of the first and the second W.-S. ladders corresponding to wells separated two-three periods apart and being nearby the resonant condition. The resonance provides high value of the transition matrix element that gives value of THz amplification coefficient up to 200-300 cm⁻¹ for the doping 5–10×10¹⁵ cm⁻³. This value is substantially higher than the one for THz quantum cascade lasers and allows to use in the lasers simple n+-SL-n+ waveguide. Some observations on transport in the SLs are given.

1. Introduction
At the beginning of 70s three proposals to use semiconducting SL to generate high frequency electromagnetic radiation appeared [1–3] – figure 1. These are: Esaki-Tsu oscillator (1) and the two of Kasarinov & Suris (2 and 3) laser proposals. The Esaki-Tsu oscillator is population inversion free system (cf. though [4]) with herewith low enough negative conductivity existing up to the Bloch frequency [5]. The Kasarinov & Suris systems are simple laser system with intrawell population inversion provided by electron injection from nearby well (2) or by universal interwell interlevel mechanism due to quasi equilibrium electron distribution in each well (3). This latter system may be considered as a system with optical transition between W.-S. ladders (shown in the case 2 in figure 1) and provides also high tunability by applied voltage. Unfortunately all these simple source schemes turn out to be unusable because of inherent static negative conductivity (NDC) leading to formation of inhomogeneous electric field domains.

To overcome domain formation and other issues the quantum cascade laser (QCL) scheme was introduced [6] leading to creation of mid IR [6] and THz [7] QCL. Since then outstanding advance in QCL occurred which is surveyed at this Conference by C. Sirtory. In all of the QCL schemes the injection inversion mechanism with almost fixed (weakly tunable) transition frequency was employed while the universal mechanism stayed intact.

In attempts to overcome domain formation in Esaki-Tsu scheme the weak barrier SLs with strong interminiband tunneling were introduced [8]. For these SLs there is a possibility to have dynamic NDC (though once again with small value like in the Esaki-Tsu case) nearby the Bloch frequency at the rising portion of SL current-voltage curve [8]. And in experimental study of transport in such SLs [9-11] we came across a possibility (a lasing scheme) to use such SL in the modified version of Kasarinov & Suris (2) scheme [12]. And this paper devoted to a discussion of this scheme and related transport measurement results.
2. The Wannier-Stark laser scheme

The essence of the scheme can be understood from figure 2 where different transitions between levels of the first and the second W.-S. ladders are shown. Experiments ([10-13] and discussed below) show the existence of long-range tunneling (several SL periods) in studied weak barrier SL near the resonance values of electric field which correspond to aligning of W.-S. levels originating from different minibands. In such resonant situation matrix elements of transitions between aligned levels become large due to long distance between wells where these levels are located. Simple consideration shows [12] that at the resonance matrix element of the transition is equal to a half of the distance between the resonant levels. On the other hand, there is natural inversion between levels of first and levels of second W.-S. ladders, when the level of the first ladder lies higher than (less populated) the level of the second ladder located in another well (figure 2, arrow labeled \( \Delta E = h\omega \)).

At the same time due to the weak barriers in the SL current is a rising function of applied voltage and domain formation is prevented. Figure 3 and figure 4 present calculation results for the transition matrix element and amplification coefficient for situation close to that shown in figure 2 for SL parameters corresponding to one of the experimentally studied SL 816 but with doping level \( 10^{16} \) cm\(^{-3} \) and scattering rate \( \nu = 5 \cdot 10^{12} \) sec\(^{-1} \) (see also [12]). We see a very high amplification coefficient that permits to use in the appropriate THz lasers simple n−SL−n+ waveguides. On the other hand with metal-SL-metal waveguide very low doped (or just undoped) SLs could be used in the lasers.
3. Transport and emission measurement results
We have studied several weak barrier GaAs/GaAlAs SL grown by MOCVD with number of periods up to 1000 (cf. [9 - 12]). Here we discuss results for the three samples: two undoped and one doped to about $10^{16}$ cm$^{-3}$. In the table 1 some properties of the SLs are given: here $d$, $w$ and $b$ are SL period, well and barrier widths, respectively, and $N_d$ is the number of SL periods. In figure 5 I-V curves measured on circular mesas for the undoped SLs are presented. The quality of these samples was high enough, as XRD and SIMS data indicate. As a result a lot of phenomena related to superlattice transport were observed (see [9 - 10]), and the main features in context of the present paper are “shoulders” at the rising portion of I-V curves. They are due (as it was established before [9, 11]) to alignment of levels of the first and the second W.-S. ladders situated several periods apart. These features establish existence of high wavefunction spread nearby the alignment voltage. No THz stimulated emission was observed on these SLs. We think that the absence of stimulated emission in this case of low doped SL is due to insufficient amplification coefficient to overcome losses in n'-SL-n' waveguide. On the other hand, if one uses metal-metal waveguide for such low doped structures, amplification could overcome waveguide losses, but we haven’t fabricated such structures yet.

| SL   | $d = w+b$, Å | $N_d$ | Doping, cm$^{-3}$ |
|------|--------------|-------|------------------|
| 426  | 185+10       | 100   | undoped          |
| 816  | 160+20       | 1000  | undoped          |
| 1410 | 135+19       | 1000  | $1.5 \cdot 10^{16}$ |

We fabricated doped SL 1410 hoping to achieve amplification coefficient higher than the waveguide losses, as calculations in figure 4 predicted. However, the quality of the grown doped SL samples was not so good: low field mobility at 4 K is about 1500 cm$^2$/V·sec (up to 10000 cm$^2$/V·sec in the undoped SL 426) supposedly due to defects in barriers (as SIMS data indicate); increase in doping itself cannot explain such mobility reduction. In the I-V curve of the SL at 4K only “hint” to a possibility of the low field Esaki-Tsu type NDC was established while in the undoped SLs a lot of phenomena related to the NDC were observed [9,10]. No THz stimulated emission was observed in this case either.

4. Conclusion
We have discussed and elaborate the new SL intraband THz laser scheme which provides high laser emission tunability by applied voltage. In this scheme, the upper lasing level is the ground state of a quantum well in SL, while the lower level is the excited state of the well located 2-3 SL periods downstream (down the applied voltage). The levels are close to resonance condition that provides high matrix element for the transition and gives high amplification coefficient which permits to use simple n'-SL-n' waveguides for lasing in doped SLs. It is important (as the transport experiments on the SLs show) that the lasing condition in the SLs correspond to rising portion of I –V curve what excludes inhomogeneous electric field formation under lasing.

Specifically the scheme was elaborated for THz range and for GaAs/GaAlAs SLs. At the same time it should work at other A3B5 material systems, at shorter wavelength and also at Si-GeSi [111] SL. Due to weak (short) barriers with low fraction of Ge the W.-S. laser scheme looks easier to realize compared to the Si-Ge/Si QCL schemes discussed nowadays.
Experiments conducted on both doped and undoped SL samples have shown the existence of features connected to the elaborated laser scheme, but we haven’t seen the stimulated emission from these SLs yet.

Figure 4. Frequency dependence of amplification coefficient for 2 different values of voltage drop on one SL period.

Figure 5. I-V curves for 426 and 816 SLs. Shoulders due to W.-S. level alignment: 1-2(4) – A, 1-2(3) – B and 1-2(2) – C are indicated by arrows.

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