Transport and stimulated THz emission in simple weak barrier superlattices

A A Andronov\textsuperscript{1}, A V Ikonnikov\textsuperscript{1}, K V Maremianin\textsuperscript{1}, V I Pozdnykova\textsuperscript{1}, Y N Nozdrin\textsuperscript{1}, A Marmalyuk\textsuperscript{2}, A Padalitsa\textsuperscript{2}, M Ladugin\textsuperscript{3}, V Belyakov\textsuperscript{3}, I Ladenkov\textsuperscript{3}, A Fefelov\textsuperscript{3}

\textsuperscript{1}Inst. for Physics of Microstructures RAS, Nizhny Novgorod, Russia
\textsuperscript{2}Sigm-Plus, Moscow, Russia
\textsuperscript{3}«Salut», Nizhny Novgorod, Russia

E-mail: andron@ipmras.ru

Abstract. Emissions at 2.6 – 2.8 THz are observed from liquid helium cooled disk chips with metal - superlattice - metal cavities made of two low \textit{n} type doped wafers with weak barrier GaAs-GaAlAs superlattice of 1000 periods. The emissions are at 8.6 – 18.8 Volts within region of rising chip current \textit{(at positive chip differential conductivity)} that guarantees absence of inhomogeneous electric field domains. At 2.6 – 2.7 THz the emission tunable by 8 – 10 Volts voltage change is higher than the Bloch oscillations frequency; while at 2.8 THz at 12 – 18 Volts it is lower than \(\omega_B\). The THz frequency bands are measured with a cyclotron resonance filter; the band width is of about that of the THz quantum cascade laser. By using long voltage pulses the chip heating above 100 K is achieved without substantial change in chip THz emission power. We speculate that the emission is super luminescence (amplification) of whispering gallery modes in the chips as a result of inverted Wannier-Stark level transitions under bias. The results advocate development of THz and higher frequency sources based on such simple superlattices; the sources should well compete with the THz quantum cascade lasers in particular at elevated temperatures.

1. Introduction

The Bloch superlattice oscillator – the THz and other frequency source at frequencies about the Bloch frequency \(\omega_B\) (figure 1a) and tunable by applied voltage in simple superlattice (SL) consisting just of periodic system of quantum well (QW) and barriers is quite old dream of heterostructure physics community. The name “The Bloch oscillator” first appeared in work by Esaki and Tsu [1] where direct current negative differential conductivity (DC NDC) for transport in SL in lowest miniband was calculated. The Bloch oscillator was given support in work by Ktitorov, Simin and Sandalovskii [2] who found peak of NDC nearby \textit{(below)} the Bloch frequency \(\omega_B\). Still so far the oscillator has not been demonstrated in particular because the NDC peak value is not generally high enough comparing with DC NDC to suppress space-charge instability in SL \textit{(produced by DC NDC)} and excite electromagnetic wave. Further development in SL transport and NDC was made by Kazarinov and Suris [3]. They proposed two lasing schemes in SLs with several SL minibands involved. These proposals also failed to provide high frequency sources due to problem of appearance of inhomogeneous electric field domains resulting from DC NDC [4]. The domain problem was solved in quantum cascade lasers (QCLs) (see e.g. [5-7]) by introduction SLs with complicated periods (cascade) and lasing due to injection to upper transition levels like in one of the schemes in [3].
Figure 1. Miniband energy $\varepsilon(k)$ in SL Brilluoin zone in electron wavenumber $k$ region $(-\pi/d, \pi/d)$, $d$ is superlattice period. (a) High minigap with miniband width $\Delta$ and the Bloch oscillations $(A' - A)$ in electric field $E$ with the Bloch frequency $\omega_B = eE d / h$. (b) Narrow minigap superlattices with tunneling through minigap to second miniband with probability $P = \exp(-E_T/E)$. $E_T \sim \varepsilon_{gap}^2$ is the characteristic tunneling field. The probability determines increase of current with electric field and mechanism of dynamic NDC.

Another way to stop the domains was proposed in [8]: SLs with weak barriers (with low minigaps). Here at high enough electric field interminiband tunneling (figure 1b) provides current growth with field that prevents appearance of DC NDC and the domains formation at such fields. By using simplified quasi classical approach NDC at frequency higher than $\omega_B$ was found in such SLs outside DC NDC [8]. This dynamic NDC originates from electron bunching in the first miniband due to electric field $E$ dependence of tunneling probability (figure 1b). With the electric field $E$ consisting of DC field $E_{DC}$ and time $t$ dependent AC field $E_{AC} = E_0 \cos \omega t$ ($E = E_{DC} + E_{AC}$) the tunneling is opened or is closed a little bit at different phases (different times) of AC field. As the result together with the Bloch oscillations bunching of electrons in the low miniband (modulation in AC electron momentum occupation) occurs and the dynamic NDC at frequencies higher than the Bloch frequency can emerge. This quasi classical consideration gives current-voltage and NDC picture shown in figure 2. Here both Esaki-Tsu DC NDC and Dynamic NDC (DNDC) outside DC NDC region are shown.

Figure 2. Scheme of $I$-$V$ curve of weak barrier SL produced by the Bloch oscillation, inter miniband tunneling and scattering (a) and frequency dependences of real part of differential conductivity $\sigma$ for the two voltage values $A$ (b) and $B$ (c) corresponding to DC NDC and negative conductivity nearby the Bloch frequency $\omega_B$ (b) and without DC NDC and DNDC at $\omega > \omega_B$ due to inter miniband tunneling (c) [8].
Soon after work [8] experiments on such weak barrier SLs were performed [9] which found important additions to the quasi classical picture: “shoulders” at rising portion of I–V curve (figure 3) due to resonant tunneling in electric field between ground level and excited level in SL QW separated by several SL periods [9,10]. Such resonant tunneling should also influence NDC regions and values. Though such tunneling resonances in SLs with strong barriers are well known, in weak barrier SL the resonant tunneling over several SL periods can exist. And indeed shoulders due to the tunneling up to 8 periods were found in the SL I–V curve and by I–V curve optical modulation [10–12]. From these observations ideas to put in operation THz laser [13–15] based on “universal” population inversion mechanism with upper lasing level being ground level in SL wells (figure 4) was proposed. This lasing mechanism can be considered as an extension of second lasing mechanism of work [3] with inter well transition for the case of SL with weak barriers. The latter guaranties absence of electric field domains and high inter well optical transition matrix element for transition to several (2-3) periods. The appropriate lasing levels and electron wave-functions are not the ones in the QWs but the ones influenced by wells interaction and electric field applied. They may be found from Wannier functions in SL with electric field involved. Such states are called the Wannier-Stark (W.-S.) states and we call the lasing scheme the Wannier-Stark lasing. Due to weak barriers and inter level resonances several periods apart W.S. wave-functions spread for several periods providing high matrix element for corresponding optical transitions.

And in this paper we report on realization of this lasing idea: observation of stimulated THz emissions at 4K from disk chips made of two wafers with weak barrier GaAs-GaAlAs superlattices in region of chips positive differential conductivity. The two emissions could be distinguished: tunable by applied voltage (8.6 – 10V) THz emission (2.6 – 2.7 THz) at frequencies higher than the Bloch frequency at these voltages and THz emission at 12.8 –18.8 V with frequency at about 2.8 THz which is below the Bloch frequency at these voltages. It is natural to explain this latter emission as stimulated emission on transitions between SL W.-S. levels [13-17]. In particular simulations in [17] by Non
equilibrium Green Function (NEGF) approach at 18 V in one of SLs studied in present work show broad amplification coefficient band (about 2.5 – 3.5 THz) with peak coefficient value about 5 – 7 cm\(^{-1}\) just at 3 THz. The emission at 2.6 – 2.7 THz should be considered as a result of the Bloch oscillation and interminiband tunneling based NDC at frequencies higher than the Bloch frequency with supposed value of NDC enhancement due to related inverted W.-S. transitions.

In regions of shoulders (figure 3) in some chips DC NDC bands appear where GHz stimulated emissions are observed. The GHz emissions were discussed in [16] and they will not be touched here. We only mention here that the GHz emissions are at 7 – 10 GHz, have effect on chip DC current and are supposed to be determined by transit time though the chip thickness (alike in SL electronic devices [18]). It is important that both the GHz and THz stimulated emissions reported in present work survives at temperature higher than 100K (see supplementary materials to [15] and data below) demonstrating claimed weak effect of elevated temperature at the mechanisms of the both emissions.

2. Materials and Methods

To observed stimulated THz emissions from SL chips one should have low loss THz cavity and high enough THz amplification to suppress cavity losses. To have low loss cavity we use disk chips with metal - SL - metal waveguide. The disk support low emission losses whispering gallery modes (WGMs) [19] while metal - SL - metal waveguide provide low the Joule losses [7]. The SL chips are eventually undoped to provide high SL quality while to have not very small amplification 1000 period SLs were grown. The chips consist of n-type low doped \((N \approx 3 - 5 \cdot 10^{14} \text{ cm}^{-3})\) at 4K superlattice GaAs - GaAlAs of 1000 periods. Two wafers \(N \) 1755 and \(N \) 2239 grown by MOCVD were used for the chip fabrication. Periods \(d\) are: for SL 1755 \(d = 172 \text{ A} \) (GaAs - 153A- well. GaAl\(_{0.12}\)As\(_{0.88}\) 19A) and for SL 2239 \(d = 186 \text{ A} \) (GaAs - 165 A - well GaAl\(_{0.12}\)As\(_{0.88}\) 21A). In the both wafer etch stop layers were grown to remove substrate and to fabricate strip line Au - n\(^+\) - superlattice - n\(^+\) - Au low loss waveguide based disk resonator (figure 5).

![Figure 5](image)

**Figure 5.** Chips studied in this work. (a) Scheme of 1 mm disk chip with SL 1755 of 1000 periods and 17.2 microns thick (top) and the chip photo (bottom). It is supposed that wire connected “head” of the chip can scatter the WGM field. (b) Chips of 0.2 and 0.5 mm diameters made from 2239 wafer: just SL between two gold layers; “tails” for contacting from the one side is seen.

The resonators are produced after etching off SL substrate and etch stop (GaAl\(_{0.05}\)As\(_{0.95}\)) thin layer [7]. Instead of using standard approach used in THz QCL [7] with active wafer bonding to host GaAs substrate we developed original approach which permit bonding to any substrate (we use poly sapphire
for chips from 1755 wafer – figure 5a) or even produce chip without any bonding: just gold – SL - gold chips (figure 5b). The chips support low emission WGMs supposed to be excited: figure 6 shows calculated Joule and emission losses in 1 mm disk chips studied.

The emissions observation is performed by Ge(Ga) THz detector placed in liquid helium nearby chip with pulsed voltage applied to chip. Pulsed voltage up to 20 V and duration about 10 microseconds were usually used. The detector registers both the emission from electrons in SL and (at high or long voltage pulses) also emission due to heated chip lattice. To study emission temperature dependence pulse duration up to 500 microseconds was employed. Such pulses heat up chips to temperature above 100 K that permits to study the THz emission temperature dependence. The THz emission frequency was measured by absorbing filter employed cyclotron resonance (CR) in mercury cadmium telluride (MCT) QW placed in magnetic field between chip and Ge(Ga) detector.

![Figure 6. Mode frequencies and losses of 1 mm disk chips made of 1755 and 2239 SLs. Joule losses (mode absorption coefficient: upper line – SL 1755, lower line – SL 2239) due to metal–n' layers and effective mode absorption coefficients due to emission losses (circles) calculated via magnetic current approach [19] are shown; WGMs are the ones with lowest emission losses.](image1)

![Figure 7. Ge(Ga) detector signals and current of the SL 1755 chip. The curves in the signals are: total (squares), lattice emission registered just after end of voltage pulse (triangles) and the one without lattice emission (discs). Current oscillations in Esaki-Tsu DC NDC region at 2.3 – 5 V are shown.](image2)

3. Results

The examples of observation results are given in figures 7 – 10. In figure 7 I–V curve and Ge(Ga) detector signal for chip from SL 1755 are presented for about 10 microseconds voltage pulse duration when no substantial contribution to the detector signal from lattice emission (registered after end of voltage pulse) occurs. Similar data are for chips made of SL 2239. The detector signal due to electrons in the SL shows sharp rise at about 7.5 V after the current plateau and gradual rise in current. Figure 8 presents filtering of THz SL emission by CR in MCT QW for chips from the both wafers. At voltage 8.6 – 10 V frequencies are higher (by about 15%) of the Bloch frequency $\omega_B$ while at 12 – 18 V are lower $\omega_B$. The former could be explained (as was said above) by the dynamic THz NDC due to tunneling to upper miniband [7,8] with possible the NDC enhancement by W.-S. lasing transitions. The emissions at 2.8 THz at 12.8 – 18.8 V we consider to be due to inverted W.-S. lasing transitions [13–17]. Eventually no (low) tuning of emission frequency with voltage here should be attributed to competing absorption transition (B in figure 4, see in particular amplification calculation in [14, 17]). But the complete picture of the transitions here is still to be understood (cf. comments in [17]). Decrease of the CR absorption dip in figure 8 with rise in voltage is due to additional contribution to the detector signal from lattice emission (figure 7). Figure 9 gives overall frequency dependence on applied voltage for chips from the both wafers. Figure 10 presents example of voltage, current and Ge(Ga) pulses for the long voltage pulse. Rise of the detector signal with time and its continuation...
after end of voltage pulse is a result of chip heating and lattices emission. At the same time drop of
detector signal produces by electron in SL emission after the end voltage pulse is of about rise of the
signal at pulse beginning (where lattice emission contribution is small). This observation points to
survival of stimulated emission at high enough elevated temperature.

4. Discussion
The lasing nature of the THz emissions observed is supported by the Ge(Ga) detector signal sharp rise
at about 7.5 V where narrow THz emission lines started to be presented. These lines shown in figure 8
are only a little bit broader than the line of a THz QCL measured in the same approach. Also the CR
dips for 8 – 10 V (where contribution by lattice emission is small) are about that of the QCL pointing
to absence substantial emission frequencies outside frequency of the CR dip in the detector signal
here. At higher voltages lattice emission appears (figure 7). The CR dip decreases but its width does
not change once again pointing to survival of the narrow band of the SL emission with temperatures
rise. The observed emissions are not high (presumably due to WGMs excitation). Also we cannot
confirm its coherent nature or its effects on the chip current (as demonstrated with the GHz emission
in the same SL 1755 chips [16]) that points to near threshold of the THz amplification condition. This
is also supported by estimated [13] and simulated [17] value of amplification coefficient in the SLs
studied. In particular NEGF simulation in [17] give amplification coefficient value up to 5 – 7 cm⁻¹
that is higher than calculated Joule losses in the chips pointing to excitation of WGMs in chips:
emission losses for WGMs are substantially smaller than that of the Joule ones (figure 6).

We believe that emission observed at 8.6 – 10.0 V presumably is the first demonstration of the THz
Bloch superlattice oscillator emission and we do think that with superlattice and chip optimization (in
particular with higher superlattice doping) THz Bloch oscillators should emerge as simple universal
tunable THz sources working at elevated temperatures.

Explanation of emission at about 2.8 THz at 12.8 – 18.8 V from the same chip required additional
consideration. As it was said above it is naturally to explain the emission by the W.-S. lasing [13–17].
But seems eventually no tuning of its frequency with voltage requires more detailed explanation.
Figure 9. Observed emission frequencies versus voltage applied to chips from both 1755 and 2239 SLs determined by dip position in CR filter. Broken line represents the Bloch oscillations frequencies \( \omega_B = eEd/h \).

Figure 10. Voltage V, current I and Ge(Ga) detector signal J pulses from a chip of SL 1755. Rise of detector signal and its existence beyond the end of voltage and current pulsed is due to lattices emission as a result of strong chip heating. Still contribution to the signal from SL emission at the beginning and end of voltage pulses are almost the same indicating survival of THz SL emission at \( T > 100 \text{K} \).

5. Conclusion
Anyway the results are the first demonstration of the THz amplification in simple SL outside DC NDC region. The SLs studied are by no means optimal to produce the THz stimulated emission: they have very low doping and not low Joule losses. Still the results strongly support the stimulated nature of the emission observed and their existence at \( T > 100 \text{K} \). So the authors can well claim that the proposed route [13–17] is quite promising for creation of the THz and higher frequency sources based on such simple SLs. Such sources based on weak barrier GaAS-GaAlAs SLs with SLs and chips parameter optimization should well compete with the THz QCLs especially at elevated temperatures. The optimization must include higher SL doping (up to \( N \approx 1 – 3 \cdot 10^{15} \text{ cm}^{-3} \)), lower thicknesses of n+ contact layers (to about 0.1 \( \mu \text{m} \)). Already these changes should permit to decrease two-three times number of SL periods needed for the lasing. In particular amplification simulation of the same SL 1755 but with doping \( 10^{15} \text{ cm}^{-3} \) show [17] amplification coefficient about 25 – 30 cm\(^{-1}\) at 40 K and 3 THz supporting the above remark on possible decrease of the SL periods numbers with higher doping.

Change of the emission frequency can be achieved by change in SL period with appropriate change in barrier strength: higher frequencies need shorter period, higher barrier strength and higher applied fields. Other material system could be promising for the THz SL sources studied. In particular the THz sources based on simple weak barrier SLs made of GaN-AlGaN heterostructures look excitingly promising for the THz sources with high temperature operation (presumably up to room temperature) due to a very high polar optical phonon energy (nearby 1000 K).

Acknowledgments
The authors appreciate interest in our work by Andreas Wacker (Lund), support of work by V.I. Gavrilenko (IPM RAS), acknowledge contribution to this work by A. Andrianov and his group from Ioffe Institute, comments by S. Komiyama (Tokyo), and the SLs X-ray characterization by Yu.N. Drozdov and P.A. Yunin (IPM RAS).

The work was supported by Grants from RAS Programs and from RFBR Grant 15-02-05503-a.

References
[1] Esaki L and Tsu R 1970 IBM Jour. Res. Dev. 14 61
[2] Ktitorov S A, Simin G S and Sandolovski V Ya 1971 Sov. Phys.-Solid State 13(8) 1872
[3] Kazarinov R F and Suris R A 1971 Sov. Phys. Semicond. 5 707
[4] Esaki L and Chang L L 1974 Phys. Rev. Lett. 33(8) 495
[5] Faist J et al 1994 Science 264 553
[6] Kohler R et al 2002 Nature 417 156
[7] Williams B S, Kumar S, Callebaut H and Hu G 2003 Appl. Phys. Lett. 82(11) 2124
[8] Andronov A A, Nefedov I M and Sosnin S V 2003 Fizika i Teknica Poluprovdnikov 37(3) 378
[9] Andronov A A et al 2003 Physics-Uspekhi 46(7) 755
[10] Andronov A A, Dodin E P, Nozdrin Yu N and Zinchenko D I 2008 Phys. Stat. Sol. C 5(1) 190
[11] Andronov A A, Dodin E P, Zinchenko D I and Nozdrin Yu N 2009 Semiconductors 43(2) 228
[12] Andronov A A, Dodin E P, Zinchenko D I and Nozdrin Yu N 2009 J. Phys.: Conf. Ser. 193 012079
[13] Andronov A A et al 2010 Quantum Electronics 2010 40(5) 400
[14] Andronov A A, Dodin E P, Zinchenko D I and Nozdrin Yu N 2013 Semiconductors 47(1) 63
[15] Andronov A A, Dodin E P, Zinchenko D I, Nozdrin Yu N, Marmalyuk A A and Padalitsa A A 2011 Active zone of a generator on semiconductor structure Russian Patent 2415502
[16] Andronov A A et al 2015 JETP Letters 102 207
[17] Winge D O, Frianckie M and Wacker A 2016 AIP Advances 6 045025
[18] Eisele H, Khanna S P and Linfield T Y 2010 Applied Phys. Lett. 96(7) 972101
[19] Andronov A A, Dodin E P, Nozdrin Y N, Pozdnayakova V I., Sadofiev Y G and Fefelov A G 2016 Electronics Letters 52(5) 383