THz Generation of Bloch Oscillators from SiC Structures due to Strong Electric Fields

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Abstract— We report on the observation and studies of the THz electroluminescence from 4H-SiC, 6H-SiC and 8H-SiC n^+-n^--n^+ structures with natural superlattice under electrical field applied along the natural superlattice axis (along the C-crystal axis). It is shown that there are two channels of the terahertz electroluminescence, which are responsible for the narrow emission lines at 5.3–12.7 meV and wider lines at 13 meV. The first emission channel can be well explained by the optical intraladder transitions in the Bloch oscillations regime. Presumably, the second emission channel is caused by optical interladder transitions between the states in different Wannier-Stark ladders.

1. INTRODUCTION

When electric field F is applied to an electron in periodic potential with period d, its translation motion can be transformed into oscillatory motion [1] with frequency ω given by

$$\omega = eFd/\hbar. \tag{1}$$

where e is an electron charge.

For one-dimensional periodic potential the dependence of the electron energy E on its wave vector k is also periodic. When electron, experiencing acceleration under applied electric field reaches the edge of Brillouin zone it group velocity changes the sign and electron starts to move back. Such oscillatory motion, named as Bloch oscillation (BO), and that defines the threshold values of electric field F_t [1]

$$W = eF_t l, \tag{2}$$

where W is a width of conduction band and l is the mean free path of electron.

Some evidence of BO and corresponding THz radiation were obtained by optical techniques in biased artificial superlattices under band-to-band excitation by femtosecond laser pulses [2]. In these experiments THz emission in the form of few cycles of rapidly damping THz electromagnetic oscillation has been observed. There is an alternative explanation of such emission as a quantum beating of the states in Wannier Stark ladders [3]. The damping of such oscillation takes place in 2–3 order faster than BO.

2. EXPERIMENT

The novel idea of the present work is that BO regime can be realized in the natural superlattice (NSL) of silicon carbide (SiC) polytypes with strong bias electric field. It should be note that there is no heterointerfaces in the SiC NSLs. The superperiodical SiC polytypes is self-organized along the C-axis and this is absolutely stable phenomenon with precise crystalline parameters [4]. The period of SiC NSL, d, is equal to $c/2$ [5], where c is the size of unit cell along C-axis, and for 4H-, 6H-, 8H-polytypes the periods are 5, 7.5 and 10Å, respectively. Experimental data testifying about minizone spectrum in SiC polytypes have been obtained previously [6]. The existence of minizone spectrum in SiC polytypes was supported theoretically in Refs. [7, 8] In the Ref. [6] it was reported about the negative differential conductivity (NDC) caused by BO regime and Wannier-Stark localization. The Ref. [9] reported about the first experimental observation of the intense THz electroluminescence caused by BO regime in SiC NSL.

The current paper is aimed to study of the THz emission associated with the BO in NSL in different hexagonal polytypes of silicon carbide 4H-SiC, 8H-SiC and in 6H-SiC at largest field . The main goal of the current paper is to present the certain proof of the existence of BO using the comparative analysis of the THz EL in three NSLs.

It can be seen that, at low temperature concentration of free electron in SiC is negligible and for observation of BO electrons should be injected into active area from adjacent highly doped emitter.

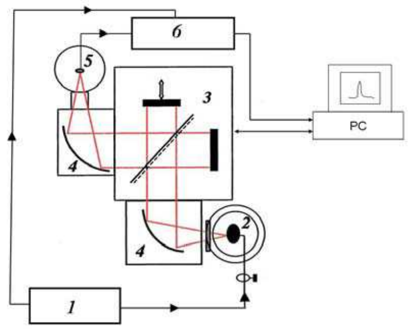


Figure 1: The schema of the measurement setup for investigation of THz electroluminescence spectra from SiC NSLs. 1 — the generator of electrical pulses; 2 — helium optical cryostat, which was optimized for the THz spectral domain, with sample; 3 — Michelson interferometer; 4 — parabolic mirrors; 5 — silicon bolometer, 6 — lock-in amplifier.

The detailed description of the studied unipolar n^{++}-n^{-}-n^{+} diode mesa-structures can be found in Ref. [9]. The setup for spectral measurements is shown on Fig. 1.

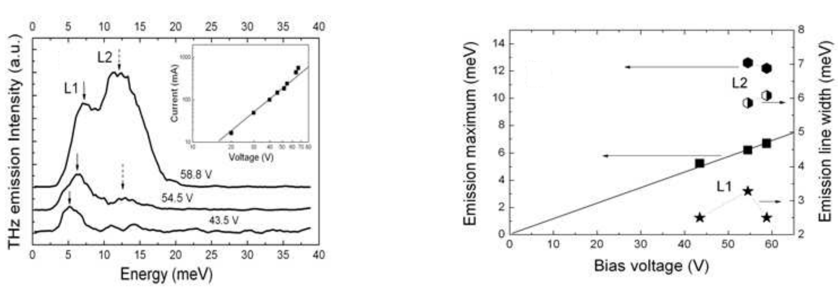
The structures fabricated on the n^{+} substrate was attached to the insulating heat-conducting p-SiC plate by the thin silver layer using a thermo compression. It allowed us to improve the thermal contact and to increase the applied electric power by 40% without any noticeable Joule heating of the active region of the n^{++}-n^{-}-n^{+} and bipolar n^{++}-π-n^{+} structures comparing with results of Ref. [9].

Impact ionization of nitrogen in n^{++}-n^{-}-n^{+} 4H-SiC structures [10] occurs at electric fields up to 50 times smaller than threshold electric fields of Bloch oscillations obtained from (Eq. (2)). Therefore bipolar n^{++}-π-n^{+} structure analogical to reported earlier [6] was used for observation of the THz BO emission from 4H-SiC.

As it was pointed out in Ref. [9] the sizable broadening of the THz emission line takes place at applied voltage 255 V as compared with that at 240 V. It was explained hypothetically by the lattice heating, but the occurrence of the weak high energy emission line with the maximum at 13.0 meV remains unexplained. For that reason we have not increased the current and voltage applied until the heat sink improvement mentioned above.

3. DISCUSSION

Figure 2(a) shows luminescence spectra of n^{++}-n^{-}-n^{+} mesa structures for different applied voltage. These spectra consist of the single, symmetrical emission lines L1 with the maximum at 5.18–7.5 meV and the spectral width of 3.0-meV.



(a) (b)

Figure 2: (a) Spectra of the THz emission from a n^{++}-n^{-}-n^{+}8H-SiC NSL at different bias voltages and at $T \sim 7$ K. The figure insert shows a typical I-V characteristic of the n^{++}-n^{-}-n^{+}8H-SiC NSL. Points are experimental data. The solid curve is the result of approximation of the data by a power law ($I = const \propto V^{2.5}$). (b) The result of decomposition of the experimental spectra by two Gaussian lines for different bias voltages. The solid line is a linear fit of the L1-line peak position versus the bias voltage.

The peak energy of 5.2 meV corresponds to electric field magnitude of 5.2×10^4 V/cm (Eq. (1)). The value of the electric field F shows also that only a part (about 35%) of the bias voltage drops on the active region of the structure. It is worth to note also that the spectrally integrated THz emission peak power was about 3.5 μW and 10 μW at 9.1 W of peak pumping power for 8H-and 6H-SiC NSLs, respectively. Such a ratio of the emission powers in reasonable agreement with the theory of THz BO radiation from SiC NSLs [9].

It is worth to note that the electric field of the THz BO emission appearance of the order of 5.2×10^4 V/cm is 1.6 times less than that for 6H-SiC NSL. This difference in electric fields is caused by the difference in the width of the first minibands in 6H-SiC and 8H-SiC 260 and 140 meV respectively [6] and it is in accordance to (Eq. (2)).

The electric field F required for appearance of THz EL correlates with the threshold field F_t of NDC [6] taking into account the temperature difference of the BO threshold field. The width of the THz emission lines remains practically unchanged in the voltage range from 43.5 to 58.8 V (Fig. 2(b)). This indicates that the electric field is practically homogeneous in the active region of the structures. Increase of the voltage till 54.5 V (corresponding to electric field 6.2×10^4 V/cm Eq. (1)) leads to a shift of the emission lines L1 to higher energy (Fig. 2(b)) and to an appearance of the second emission line L2 centered at energy 12.9 meV. Further increase of the voltage, till the value 58.8 V is accompanied by sharp rise of electrical current and intensity of second line, which became dominant in the spectrum. The width of the second line at 58.8 V is about 7.0 meV and energy maximum lies near the 12.5 meV.

It was found that the THz EL from side face of the mesa structure is linearly polarized along the C-crystal axis (along the electric field) and the polarization degree is about 56%.

The current through the structure is proportional to voltage in the 5/2 power in accordance with the theoretical result for the I-V characteristics in BO regime [9]. The dependence of the intensity of EL on the current is almost linear.

The low energy shift of the spectral peaks in the 8H-SiC NSL THz emission comparing with that for 6H-SiC NSL is the consequence of the quantitative differences in miniband widths of 8H-SiC and 6H-SiC. This is convincing proof of the realization of the BO regime in these NSLs

As a surprise in this study the strong electroluminescence line comes at 12.5 ± 0.1 meV. The intensity of this line superlinearly increases with current as $P \sim I^{2.5}$.

As mentioned above, the relatively week line at 13.0 ± 0.1 meV have been observed in 6H-SiC THz EL spectra too [9]. Fig. 3 demonstrates two spectra of the THz emission of 6H-SiC at 255 V (shown before in Ref. [9]) and the spectrum at 295 V obtained in the current work. It is clearly seen that the L2 lines with the maximum near 13.0 meV grows drastically with the pump power increase as $P \sim I^7$.

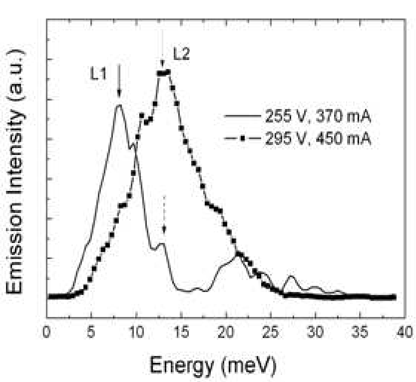


Figure 3: Spectra of the THz emission from the NSL 6H-SiC n^{++}-n^{-}-n^{+} structures.

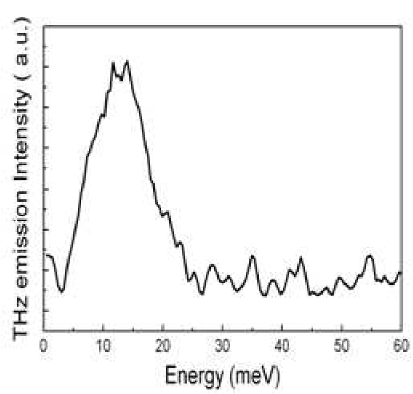


Figure 4: The THz emission for a 4H-SiC bipolar n^{++}-π-n^{+} structure at the bias voltage of 30 V and the current of 1150 mA. $T \sim 7$ K.

The full spectrum width increase at 295 V can be substantially explained by the superposition of two lines: at 9.5 meV (extrapolated transition energy of the L1 at 295 V) and 13.0 meV L2 rather than the line broadening due to the heating and field increase. Although it should be mentioned that L2 is 1.7 times wider than L1. It should be emphasized that the detection of L2 in the THz EL spectra of 6H-SiC NSL becomes possible after currying out the investigations of 8H-SiC NSL, which has the well-resolved THz EL in the 7.5–12.9 meV range (Fig. 2(a)) and it has allowed us to make a statement (see Fig. 2(b)) that the L2 line is not directly related to the THz BO emission. However, it can occur at the conditions of electron Wannier Stark localization in a degenerated states system of neighboring conduction band minimum in K point [8].

The total emission power of the THz emission at 295 V is about $P = 4 \times 10^{-5}$ W. It is in five orders more than the estimation of the black body emission power with the maximum at 13.0 meV ($T = 30$ K).

So, both in 6H-SiC and 8H-SiC NSLs we have revealed the strong emission lines, marked by L2 in this paper, which are very similar in their behavior.

Figure 4 shows the spectrum of THz emission from 4H-SiC bipolar n^{++}-π-n^{+} structure. There is a single broad peak centered at 12.8 ± 0.5 meV ($F = 250$ kV/cm) with width 11 meV. The voltage applied between two n^{+} — areas was 30 V, and the current reaches 1150 mA. The sample based on 4H-SiC has the highest threshold electric field required for observation of THz emission, and the highest current. Due to high level of current the sample demonstrated rapid degradation. For that reason only one spectrum has been obtained and the same analysis as for 6H-SiC and 8H-SiC was not possible. However, as is seen the spectrum shows a broad emission line centered at 12.8 meV with spectral width of 11 meV. It is quite possible that such a broad line is associated with the superposition of two lines having the same nature as it was mentioned above, which, however, for 4H-SiC are arranged substantially closer to each other than in 6H- and 8H-SiC.

It was experimentally established that the peak energy of EL in the 8H-SiC n^{++}-π-n^{+} structures is 1.5 times greater than for n^{++}-n^{-}-n^{+} structures. According to these arguments the spectrum peak in n^{++}-n^{-}-n^{+} 4H-SiC structures will probably be near the 8.4 meV energy that would correspond to the $F = 168$ kV/cm electric field inside the NSL(see Eq. (1)).

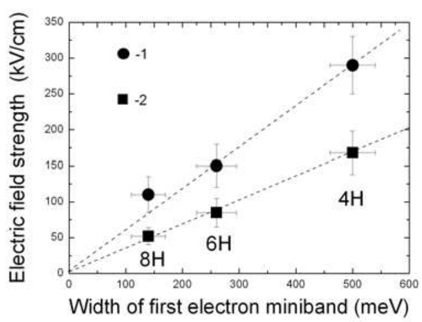


Figure 5: The dependence of the threshold field for the negative differential conductivity (1), obtained before at 300 K [6] and the minimal electric field required for the observation of the THz BO emission (2) at 7 K (Ref. [9] and present work) on the first miniband width in the 8H-, 6H- and 4H-SiC NSLs. The dashed lines are linear fits of the experimental data.

The threshold fields for the NDC and the THz emission correlate well for 4H-, 6H- and 8H-SiC NSLs. Fig. 5 shows the dependence of the threshold electric field for the observation of the NDC at 300 (Fig. 5, (1)) and electric field required, for the observation of THz emission at 7 K (Fig. 5, (2)) on the first minizone width in the 4H-, 6H- and 8H-SiC NSLs. The both dependencies are linear that is yet another proof of BO nature of these effects as far as it corresponds to Eq. (2) at practically the same mean free paths for electrons in 4H-, 6H- and 8H-SiC NSL. The experimental results indicate that for $l = 170$Å and 310Å for 300 and 7 K, respectively.

4. SUMMARY

Thus, the BO regime was realized in the natural superlattices 4H, 6H and 8H-SiC on the U-line (M-L) parallel to the C-axis of the hexagonal Brillouin zone. It is established that intense THz emission can be attributed to the intraladder transitions between the Wannier-Stark states and has all characters of the BO effect.

As a result we can state that NSL SiC is a source of the electrically tunable terahertz emission in the 1.6–2.3 THz and in the 3.2 THz ranges.

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