# A Frequency-Selective Terahertz Radiation Detector Based on a semiconductor Superlattice with a Resonator

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ABSTRACT — WE PROPOSE THE NEW DESIGN OF THE TERAHERTZ DETECTOR, WHICH MUST HAVE FREQUENCY SELECTION PROPERTY AND OPERATE AT ROOM TEMPERATURE. THE IDEA IS BASED ON A STANDING WAVE ENHANCEMENT OF DETECTOR RESPONSIVITY. THE DETECTOR CONTAINS LATERAL SEMICONDUCTOR SUPERLATTICE, BROADBAND BOW TIE THZ ANTENNA AND THZ RESONATOR. AS COMPARED WITH WELL-KNOWN VARIANT WE CHANGE A TECHNOLOGY OF ANTENNA ATTACHMENT TO THE SUPERLATTICE THAT ALLOWS ADDITIONALLY GROWING UP THZ RESONATOR. WE PERFORMED NUMERICAL ANALYZE OF THE STRUCTURE BASED ON THE RELAXATION TIME APPROXIMATION OF ELECTRON TRANSPORT IN SUPERLATTICE AND WAVE LINE DESCRIPTION FOR MATCHING BETWEEN ANTENNA AND SUPERLATTICE. WE CHOOSE THE SUPERLATTICE PARAMETERS, WHICH ARE TECHNICALLY AVAILABLE TODAY AND SHOW THAT THE DETECTOR RESPONSIVITY CAN BE ENHANCED IN SEVERAL HUNDRED TIMES IN COMPARE TO WELL-KNOWN EXISTENT VARIANT OF A SUCH DETECTOR, ALSO THE FREQUENCY SELECTION QUALITY CAN ACHIEVE A VERY HIGH VALUE (F/_F~$10^3$).

Terahertz (THz) electromagnetic radiation has recently found increasing prominence in various fields of science and technology. This includes sensing where it is ideal for identification of biological micro species, communications, in which several orders of magnitude of increase in bandwidth as compared with current wireless technology is expected; and in detection, in which it is capable of identifying metal objects of millimeter size and hidden from view. One of the major obstacles preventing widespread applications of terahertz technology is the lack of powerful, tunable sources, and sensitive detectors in this frequency regime of the electromagnetic spectrum. One of the possible solutions to create a sensitive THz detector is exploitation of an extremely strong nonlinear dispersion relation for the electrons in the limit of a single miniband of a semiconductor superlattice at room temperature [1]. In this article we propose a novel radiation detector in the terahertz region of the electromagnetic spectrum based on semiconductor superlattice with a resonator that was forethought for the frequency-selective detection.

On the fig.1 we sketched possible design of the frequency-selective THz radiation detector.

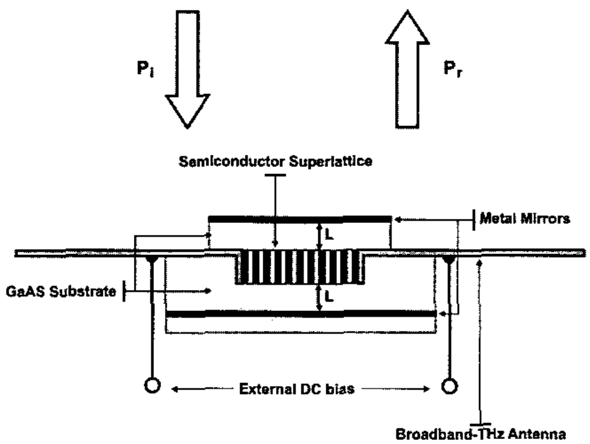


Fig. 1. The proposed THz detector design.

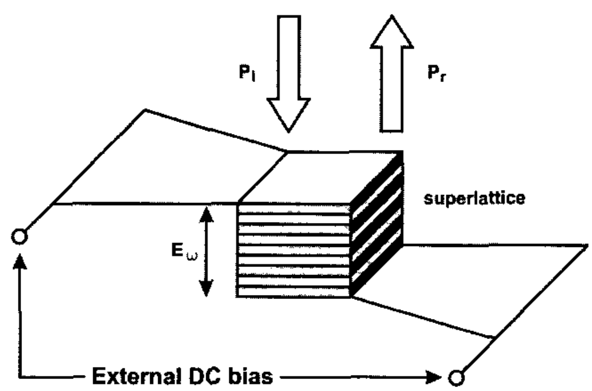


Fig. 2. The existent superlattice THz detector.

The detector contains lateral semiconductor superlattice (GaAs/AlGaAS), broadband bow-tie THz receiving antenna and resonator formed by two metal mirrors. Making process of the proposed detector is possible by

means of MBE- technology, because the structure allows vertical layer growing. As compared with well-known existent variant that is sketched on the fig.2 we change a technology of antenna attachment to the superlattice that allows additionally growing up THz resonator. The GaAs substrate serves as resonator infill. The main point of our design is that structure geometry allows a polarization of exited by incident wave superlattice current to be parallel to the metal mirrors that must lead to effective pumping of THz resonator.

The physical meaning of the suggested design is enough understandable. Obviously that for certain frequencies of incident radiation superlattice is situated at mode maximum of the resultant self-consistent field of the standing wave generated due to effective field excitation in resonator. The internal superlattice THz field induces a dc current change, which is registered in the external circuit. The relation between the induced dc current and internal THz field is well known in _ relaxation time approximation for electron transport and written in the following form [2]:

$$\_I_{dc} = (1/4)|V\_|^2 F_2(\_,V_{dc}) , \qquad (1)$$

where $V\_ = E\_Nd$ is the THz voltage across the superlattice perpendicular to the layers ($E\_$ is the THz electric field), N is the number of periods in the superlattice sample, d is the superlattice period,

$$F_2(\_,V_{dc}) = -(4I_p/V_p^2)(V_{dc}/V_p)[3+(\_)^2-(V_{dc}/V_p)^2]\_$$

$$\{[1+(V_{dc}/V_p)^2][1+(\_+V_{dc}/V_p)^2][1+(\_-V_{dc}/V_p)^2]\}^{-1} ,$$

$V_{dc}=E_{dc}Nd$ is the dc voltage applied to the superlattice ($E_{dc}$ is the dc electric field), $I_p=Sj_p$, $j_p$ is the peak current density, $S=\pi a^2$ is the area of the superlattice , a is the superlattice mesa radius, $V_p=E_pNd=N\_/e$ is peak electric voltage, at this voltage current density in superlattice reaches its maximum (peak) value $j_p$, $\_=1/\_$ is the electron's collision frequency, _ is the characteristic frequency of the incident radiation, e is electron charge.

The responsivity of such a detector is determined by the standard expression as the module of the current change $\_I_{dc}$ induced in the external dc circuit per incoming ac signal power $P_i$

$$R = |\_I_{dc}|/P_i , \qquad (2)$$

Theoretical prediction of the dependence of the frequency-selective THz radiation detector on its technical parameters is the main task of this article. To solve this task we describe the process of interaction between incident wave and our detector by use of the equivalent wave-line description. The same approach was applied in [2] where the authors found the expression for responsivity of the well-known superlattice detector solving wave task with the appropriate equivalent circuit modeling. This approach showed in [3] the perfect coincidence between experimental and theoretical responsivity dependences.

The equivalent to our frequency-selective detector wave-line is sketched on the fig.3.

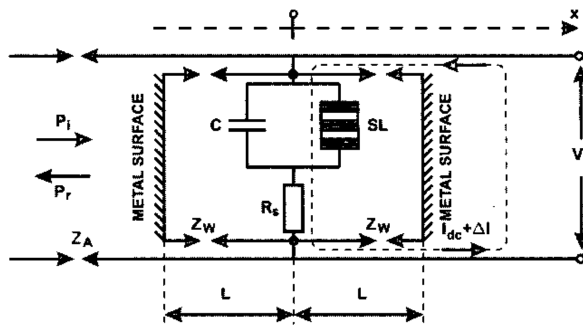


Fig. 3. The equivalent to the proposed wave line.

The equations system for all propagating waves taken at the superlattice position (x=0) is following:

$$U_i+U_r = U_{i1}+U_{r1} = U_{i2}+U_{r2} , \qquad (3.1)$$

$$U_{i1}e^{ikL}+U_{r1}e^{-ikL} = U_{i2}e^{-ikL}+U_{r2}e^{ikL} = 0 , \qquad (3.2)$$

$$[(U_i-U_r)/Z_A]+[(U_{i1}-U_{r1})/Z_W]-[(U_{i2}-U_{r2})/Z_W] =$$

$$[(U_i+U_r)/Z_C] , \qquad (3.3)$$

where $U_i$ , $U_{i1}$ , $U_{i2}$ , $U_r$ , $U_{r1}$ , $U_{r2}$ are voltage amplitudes of the all six wave existing in the system ($U_i$ is a voltage in the incident wave upon broadband antenna of the detector, this wave is propagating toward x-axis, $U_r$ is a voltage in the wave reflected by our detector and propagating backward x, and etc.); $k=\_\_^{1/2}/c_0$ is the module of the wave vector in the GaAs resonator infill, $\_=12.9$ is the dielectric constant for GaAs, $c_0$ is the light velocity in vacuum; $Z_A$ , $Z_W$ are wave impedances, $Z_W=377/\_^{1/2}$(Ohm); $Z_C=R_s+1/(G_{AC}+i\_C)$ is the effective impedance at superlattice position; C is the capacitance of the superlattice, $R_s$ is the resistance of the parasitic high-frequency losses; $G_{AC}$ is the superlattice ac conductance [1]:

$$G_{AC} = (2I_p/V_p)[1+i\_\_-(V_{dc}/V_p)^2]\_$$

$$\{[1+(V_{dc}/V_p)^2][(1+i\_)^2+(V_{dc}/V_p)^2]\}^{-1} , \qquad (4)$$

The equations (3.1) and (3.2) are the boundary conditions at x=0 and metal mirrors: the equation (3.3) is the

equation for currents. Using equations (1), (2), (3) and (4) we obtain the expression for the responsivity of the frequency-selective THz detector:

$$R=[2|F_2(2\pi f,V_{dc})|/Re(1/Z_A)]\cdot|(G_{AC}+i2\pi fC)^{-1}\_\ [R_s+(G_{AC}+i2\pi fC)^{-1}]^{-1}\{1+Z_A[R_s+(G_{AC}+i2\pi fC)^{-1}]^{-1}-(Z_A/Z_W)(2i/\tan(\pi f/f_0))\}^{-1}|^2 , \quad (5)$$

where f is the frequency of the incident wave, $f_0=c_0/(2\_^{1/2}L)$ is the lowest resonance frequency of the system. The expression for responsivity of the existing superlattice detector can be obtained from (5) assuming $Z_W=0$.

Characteristic theoretical dependence of the dimensionless normalized responsivity (responsivity divided by the quantum efficiency $R_{quantum}=e/hf$) of the proposed detector on frequency of the incident radiation is shown on the fig.4 (solid line), also on the picture we show well-known normalized responsivity dependence of the existing detector (dash line) with the assumption for comparison that both detectors have the same superlattice parameters and operate at room temperature.

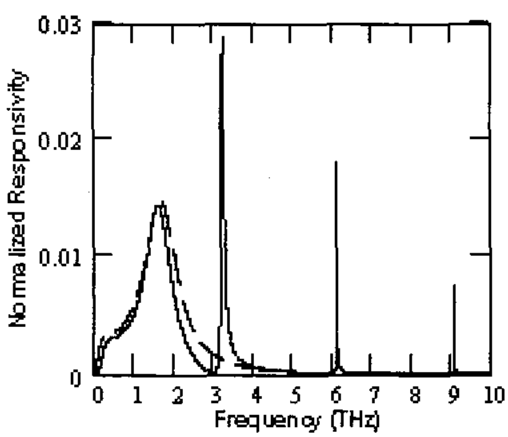


Fig. 4. The frequency dependence of the normalized detector responsivity.

We choose the following superlattice parameters, which are technically available today: superlattice period is d=5nm; number of the periods is N=100; mesa radius a=3.0_m; maximum current density is $j_p=100kA/cm^2$; relaxation frequency is f_=0.5THz; the resistance of the parasitic high-frequency losses is $R_s=0.1Ohm$. Also we choose the lowest resonance frequency is $f_0=3.0THz$ and the wave impedance of the broadband antenna is $Z_A=Z_W=104Ohm$; normalized applied bias $E_{dc}/E_p=0.7$, where $E_p=4kV/cm$ is electric field corresponding to the maximum superlattice current density. As can be seen from this two graphs that the frequency selection quality of the proposed detector at one of the bandwidth, for example at f=6.1THz, is f/_f=440 and the responsivity of the proposed detector $R_{proposed}(6.1THz)=0.72A/W$, which is about 150 times more than the responsivity of the existent detectors, which typically have $R_{existent}(6.1THz)=0.005A/W$, but we should notice that minimal characteristic detection time $\__{min}$, which is a time needed to register the incident signal, with the responsivity given by the expression (5), will be different for the proposed and existent detector. For the existent detector that time is in order of electron's collision time $\__{min}^{existent}=(1/f\_)\approx 2\_10^{-12}s$; for the detection with the enhanced responsivity by proposed nanostructure that time can be estimated as $\__{min}^{proposed}=(1/\_f)+(1/f\_)\approx 7\_10^{-11}s$ for the chosen structure parameters.

In conclusion, we have proposed the new design of the THz superlattice detector, which must have frequency selection property and operate at room temperature. We have calculated the current responsivity of the proposed detector by use of the equivalent circuit modeling and compared it to the responsivity of the existent superlattice detector with the assumption that both detectors have the same technically available superlattice parameters. We have obtained that the responsivity of the THz detector based on the superlattice can be enhanced in several hundred times by THz resonator which serves as matching circuit between the incident wave and the superlattice. Also we have counted the main characteristics of the proposed THz detector.

## REFERENCES

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