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Sn-nanothreads in GaAs matrix and their sub- and terahertz applications

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Abstract. We report on theoretical and experimental studies of gated GaAs structures like the field-effect transistor with an array of parallel Sn nanothreads (Sn-NTs) embedded into GaAs matrix. Two device structures are proposed and considered: the pseudomorphic HEMT (PHEMT) with a doping profile of Sn-NTs and the terahertz hot-electron bolometer (THz HEB) both fabricated on vicinal GaAs substrates. PHEMT demonstrates the anisotropy of drain-source current $I_{\parallel}/I_{\perp} \sim 2.5$ at 300 K when current flows along and across Sn-NTs which we relate to formation of quasi-one-dimensional conductivity channels in InGaAs quantum well. Maximum power gain cut-off frequency $f_{max} \sim 0.15$ THz is shown. The operation of THz HEB is associated with an increase in the density of the delocalized electrons due to their heating by the incoming THz radiation. The quantum and the classical device models are developed. Since the fraction of the delocalized electrons strongly depends on the average electron energy (effective temperature), the proposed THz HEB can exhibit an elevated responsivity compared with the HEBs based on more standard heterostructures. Due to a substantial anisotropy of the device structure, the THz HEB may demonstrate a noticeable polarization selectivity of the response to the in-plane polarized THz radiation.

1. Introduction

Semiconductor devices based on quasi-one-dimensional electron systems might be attractive for sub-THz and THz regimes [1]. By utilizing vicinal GaAs substrates with the surface inclined with respect to the (100) direction by the certain angle one can fabricate GaAs structures with the surface that constitutes an array of the terraces with one monolayer height (0.28 nm) and the spacing between the terraces about of 50 nm. The δ -doping of this surface by Sn atoms results in the formation of the chains of these atoms (i.e., self-assembled Sn-nanothreads – Sn-NTs) at the terrace edges. On overgrowing the obtained structure, one acquires the array of the Sn-NTs inserted in the GaAs matrix. The free electrons accumulated around each Sn-NT form highly conducting channels along the NTs. The average electron density can be controlled by the gate voltage. The conductivity along these channels and perpendicular to them can be markedly different [2,3].

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In this paper we propose and consider first pseudomorphic HEMT (PHEMT) and the lateral THz hot-electron bolometer (THz HEB) fabricated on vicinal GaAs substrates. The first utilizes InGaAs quantum well with doping profile of Sn-NTs while the second uses the gated GaAs structure like the field-effect transistor with Sn-NTs embedded into GaAs matrix as a sensing element of THz detector.

2. PHEMT fabrication and its frequency characteristics

The schematic view of the considered PHEMT is shown in Ref. [3]. The fabrication process in details is discussed in Ref. [4]. Figures 1,2 demonstrate measured I-V characteristics and frequency dependences of MSG/MAG (Maximum stable gain/Maximum available gain) and U_g (Mason's gain), respectively. As seen in figure 1 the anisotropy of drain-source current is obtained at 300 and 77 K; moreover the reduction of measurement temperature down to 77 K leads to the appearance of a negative differential resistivity, most likely attributed to the capture of the carriers by deep traps, warming up the electron gas and scatter carriers towards wide bandgap layers with smaller mobility [5]. The obtained experimental values (figure 2) are well agreed with PHEMT based on heterostructures with 20% content of InAs in InGaAs quantum well (QW) and exceeds its typical values (which are approximately 15 dB for MSG/MAG, for instance). We believe this is due to decrease of electron scattering during movement in QW along Sn-NWs, and as a result, due to higher drift electron velocity in the quasi-1D conductivity channels formed in QW. Besides, it should be pointed out that varying the width of the spacer layer, which spatially divides Sn-NWs and QW, it is possible to obtain a deeper modulation of the electron density in QW, which will result in a higher anisotropy of PHEMT characteristics.



Figure 1. Measured I-V characteristics of in strong electric fields when current flow parallel (||) and perpendicular (\perp) to Sn-NTs for 300 K and 77 K.



Figure 2. Power gain cut-off frequency f_{max} and MSG/MAG of PHEMT for parallel (||) and perpendicular (\perp) to Sn-NTs directions.

3. THz HEB device structure and operation principle

We consider THz HEB based on GaAs layer in which an array of Sn-NTs (which is a sensing element of detector) is inserted. There are the side contacts (the source and drain) and the gate electrode as schematically shown in figure 3. The operation of the proposed THz HEB is associated with the heating of electrons in the channels along the NTs resulting in an increase in the electron current perpendicular to these channels and, hence, between the source and the drain [6]. This current is created by the electrons with the energies exceeding the height of the potential barriers between the NTs. The average electron density can be controlled by the gate voltage (V_g) as seen in figure 3,c. Two device models (the classical and the quantum one) are developed: the quantum one was based on the self-consistent solution of the Poisson and Schrödinger equations, the classical model involved the Poisson equation and density of states omitting quantization. Some of simulation results (for the classical model) are depicted in figure 4.

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Figure 3. Schematic view of the proposed THz HEB (a). The potential profile (*U*) accumulated by Sn dopants for the ungated case is indicated in (b) and for the negative gate voltage (V_g) is depicted in (c) (see Ref. [2]). The vertical sizes of the calculation domain are indicated by W_g and W_s , the distance between the source and drain is shown by L_{\perp} (W_g and $W_s \gg L$).



Figure 5. Extraction from series of the measured I-V curves: the drain-source current I_{ds} vs. gate voltage at $V_{ds} = 0.5$ V for current flow perpendicular to the Sn-NTs (I_{perp}) and parallel to them (I_{par}). The inset shows the ratio of mobilities vs. gate voltage.



Figure 4. Spatial distributions of the potential energy in the source-drain direction for different gate voltages V_g at room temperature (a) and fraction of the electrons over barrier (the delocalized electrons) to all electrons $F(V_g,T)$ vs. gate voltage for two different temperatures (b). Both figures (a,b) are attached according to the classical simulation.



Figure 6. Calculated room-temperature responsivity R_w at the gate voltage $V_g = -1$ V and the drain-source voltage $V_{ds} = 0.5$ V. The noise-equivalent power (NEP) and the specific detectivity (D^*) of the THz HEB are presented.

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It should be noted that according to the experimental data (see figure 5) the two device models qualitatively demonstrate similar behavior, nevertheless, the classical one is in the better quantitative agreement compared to the quantum one [7]. Figure 6 shows the calculated responsivity (R_{ω}) for room temperature at the gate voltage $V_{\rm g} = -1$ V corresponding to the experimentally measured dark current (from I-V characteristics) with the drain-source voltage $V_{\rm ds} = 0.5$ V. As seen for the frequency $\omega/2\pi = 1.0$ THz the responsivity equals to $R_{\omega} = 2.51$ A/W that exceeds the average values for HEBs on more standard heterostructures and some uncooled THz detectors [8].

The proposed HEB may possess the polarization selectivity (i.e. sensitivity) in the plane of the incident THz radiation which is useful for practical applications. The sensitivity of polarization dependence is associated with different absorption of radiation at which electric field is directed parallel or perpendicular to Sn-NTs. This is due to a distinction in the electron dynamics (virtually free motion in the former case and localization in the latter). Evidently, the HEB might possess higher responsivity when the THz radiation is incident parallel to the NTs.

4. Conclusion

In this paper we have proposed and considered first pseudomorphic HEMT and the lateral THz hotelectron bolometer fabricated on vicinal GaAs substrates. The first utilizes InGaAs quantum well with doping profile of Sn-nanothreads (Sn-NTs) while the second uses the gated GaAs structure like the field-effect transistor with an array of self-assembled Sn-NTs embedded into GaAs matrix which serves as a sensing element of THz detector. The theoretical and experimental studies of both devices were carried out and presented.

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