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Significant noise current decrease in a terahertz photoconductive antenna-detector based on a strain-induced InAlAs/InGaAs superlattice

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We registered a significant decrease of the noise current of a photoconductive antenna (PCA), which is based on a strain-induced InAlAs/InGaAs superlattice with an ultrashort photocarrier lifetime due to a decrease in the focal spot size of a probe laser beam. We showed that the proposed PCA-detector exhibits merely a 1.5-fold increase of the noise current, while the THz power boost reaches a 10-fold magnitude. This feature can be used, in particular, to detect small THz signals. The PCA-detector shows a ~ 65 dB in its signal-to-noise ratio within 0.1−4.0 THz bandwidth.

Keywords: Terahertz frequency, photoconductive antenna, THz detector, InGaAs/InAlAs superlattice.

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Broadband spectroscopy with form registration of terahertz (THz) pulses is actively used to solve wide range of objectives [1,2]. To register electromagnetic pulses of THz-range in modern spectrometers the photoconductive antennas (PCAs) are used due to the compact design, possibility to reach high signal-to-noise ratio, as well as broad detection band [3,4]. Promising semiconductor materials, which are able to be excited by radiation of fiber femtosecond lasers, include a ternary compound InGaAs, as well as superlattice heterostructure InAlAs/InGaAs [5–7]. Unfortunately, due to high intrinsic conductance InGaAs layers have low electrical resistance, and also large life time of charge carriers (τ_{rec}), which increases power of thermal noise, and thus limits their use in PCA. The different methods of characteristics optimization of photoconductive materials based on InGaAs [8] are suggested, but the objective of noise decreasing of PCA-detector still is actual and requires search of new approaches.

In present paper we for the first time experimentally demonstrated significant decrease in noise of PCA-detector, designed based on original strain-induced InAlAs/InGaAs (SISL) when diameter of focal spot ($2b$) of laser probing decreases. SISL samples were grown by molecular-beam epitaxy. To perform the relative analysis the samples of lattice-matched superlattice InAlAs/InGaAs were additionally fabricated. The single difference between SISL and lattice-matched superlattices (LMSL) is decreasing from 52 to 38% of mole fraction of indium in the barrier layers of InAlAs to create the elastic stresses, which results in decrease in τ_{rec} from 4.4 to 1.7 ps [9], and makes SISL as an extraordinary candidate for PCA-detectors manufacturing based on InGaAs.

It is known that prevailing mechanism of noise generation in PCA-detectors is the thermal noise (I_{JN}) [10], its power in inversely proportional to the detector resistance (R_{det}). Traditionally the basic method of thermal noise decreasing is selection of high-resistance material, which is difficult to implement in case of InGaAs. During point beam focusing of probing laser pulse into the gap between electrodes (g) the integral resistance of the detector is sum of two resistances: $R_{det} = R_{dark} + R_{ph}$ — for regions of focal spot and remaining part of the photoconductor in gap, respectively. Therefore, the thermal noise dependence on the focal spot diameter occurs, which for PCA-detector based on SISL is given in Fig. 1, a. The analytical calculation using 1D model Drude model showed [3] that at $g/2b \gg 1.44$ the ratio $R_{dark}/R_{ph} \gg 1$, of the focal spot boundary was determined by intensity decrease by e^2 times. This fact, in particular, explains the observed in Fig. 1, a at $g = 20\,\mu$m proximity of the detector noise to dark noise in wide range of values *2b*. It is important to note that low values of diameter minimize the thermal noise, but due to inevitable asymmetry of electrodes or form of the focal spot the current of diffusion nature occurs (I_{diff}), see Fig. 1, b. In THz-spectrometers generally bias voltage of PCA-source is modulated [11], so I_{diff} is cut off by the synchronous amplifier, but diffusion corresponding schrot noise (I_S) leads to signal noise level increasing of PCA-detector. Numerical estimates for SISL and LMSL with parameters from paper [3] provide the following values: $I_{\text{JN}} = 7.1$ and $17.9\,\text{pA}/\sqrt{\text{Hz}}$, I_{diff} in stationary state is 5.5 and $25.6\,\mu$A, at that $I_S \leqslant 1.4$ and $2.9\,\text{pA}/\sqrt{\text{Hz}}$. It is obvious that $I_S \sim I_{\text{JN}}$, so the schrot noise contribution shall not be disregarded, and the experimental measured power of noise is $P_N \propto I_{\text{JN}}^2 + I_S^2$. At small diameter

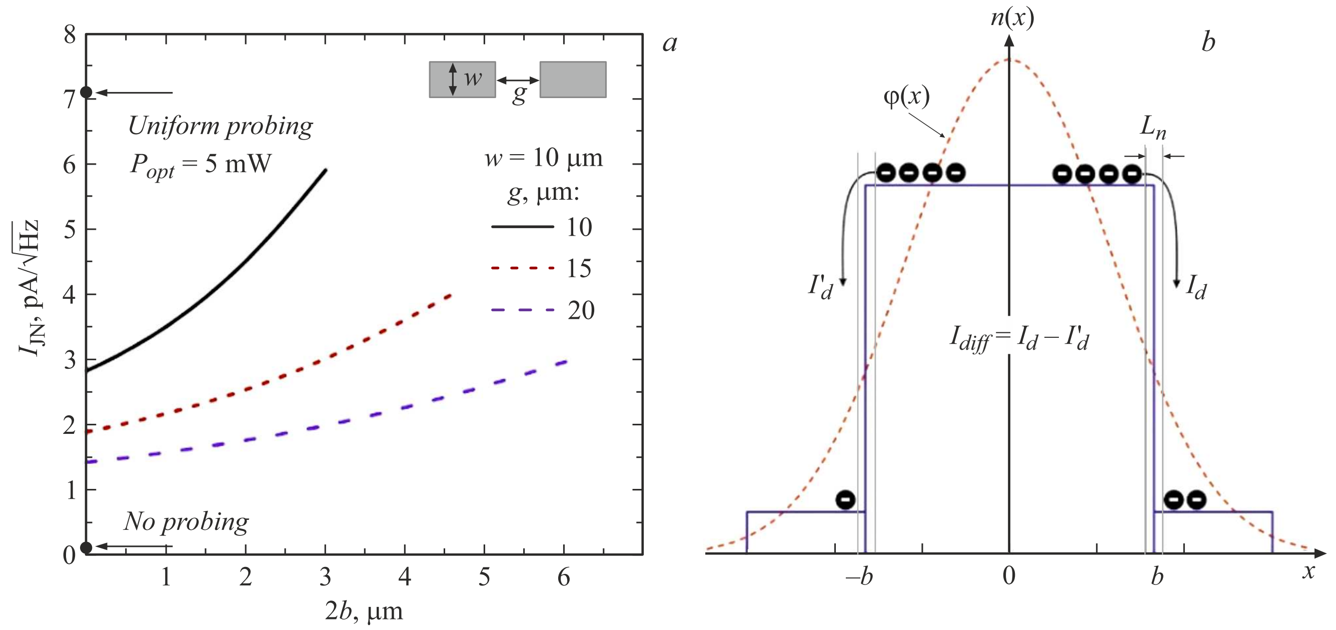

Figure 1. Thermal noise of and PCA-detector I_{JN} based on SISL at different diameter of focal spot of laser probing $2b$ (a) diagram of occurrence of diffusion current I_{diff} (b). Parameters $\varphi(x)$ and $n(x)$ — spatial profiles of laser probing beam and of concentration of electrons; $\varphi(\pm b) = \varphi(0)/e^2$.

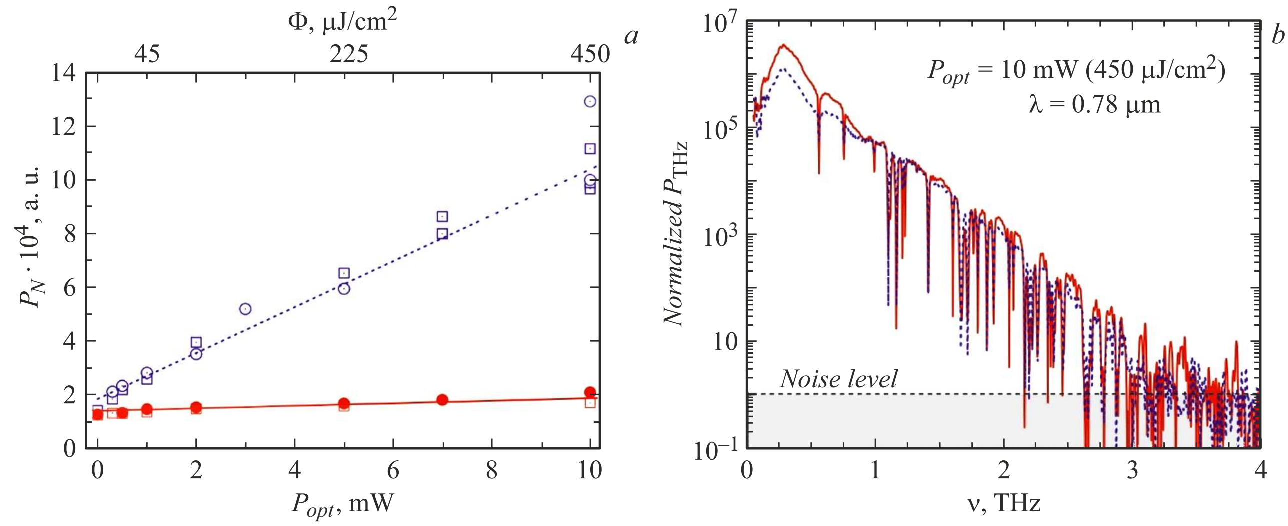

Figure 2. a — noise power P_N for PCA-detectors at different average power P_{opt} and average power density of energy of laser probing. Different symbols correspond to measurements for different types of identical samples of PCA-detectors based on based on LMSL (top curve) and based on SISL (bottom curve). b — recorded spectra of THz-radiation P_{THz}, normalized to noise level. Solid lines — measurements for PCA-detectors based on SISL, dotted lines — based on LMSL.

of the focal spot with average power increasing of the laser probing P_{opt} the detector noise P_N will increase mainly due to term $I_S^2 \propto P_{opt}$: $P_N \propto \mathrm{const} + I_S^2$, i.e. as per linear law. So, rate of noise increasing (tangent of inclination angle) is proportional to the diffusion length L_n. As the detector registered power is $P_{\mathrm{THz}} \propto P_{opt}$, the later is especially important in terms of maximization of signal-to-noise ratio during detection of weak THz-signals.

The characteristics of PCA-detectors were measured using laboratory THz-spectrometer [3,11], in which the laser with wavelength of $\lambda = 780$ nm and pulse width of 100 fs was used as radiation source. Noise power of PCA-detectors was assumed as equal to mean square of signal upon THz-radiation interlocking. The point beam focusing of the probing radiation with $2b \approx 6.6\,\mu$m ensured in experiments $R_{dark}/R_{ph} \approx 3.6$, thus minimizing the thermal noise. Shown in Fig. 2,a dependence of detector noise $P_N(P_{opt})$ for

LMSL is well described by the linear function, thus experimentally confirming the fact of presence in signal of the schrot noise I_S. Note that tangent of straight line inclination for SISL was significantly lower than for LMSL. In particular, upon probing power increasing by 10 time PCA-detector based on SISL demonstrates noise increasing by at least 1.5 times. Therefore, this original material is more effective, which is obviously demonstrated by normalized THz-spectra in Fig. 2, *b*. In particular, SISL can be used to make PCA-detectors of low power THz-signal (at level of fractions of pW). At that signal-to-noise ratio is at level of 65 dB in frequency band of 0.1−4.0 THz.

Therefore, in paper we suggested and tested by experiments the original approach to noise decreasing of PCA-detectors by use of elastically strained superlattice heterostructure InAlAs/InGaAs in combination with small diameter of focal spot of probing radiation.

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Conflict of interest

The authors declare that they have no conflict of interest.

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