Supplemental Material to the article

“Strong influence of light wavelength on quantum oscillations of photocurrent and their resonant tunneling nature in GaAs/AlAs p–i–n structures”

S1. Photooscillations at constant radiation intensity. Figure S1a shows the reverse branches of the I–V_b characteristics of experimental samples at $V_b < 1.5$ V under illumination with light of equal intensity with wavelengths in the range from 850 to 565 nm. In the absence of illumination, these I–V_b characteristics were monotonic dependences without any visible features, and the value of the dark current in the range up to 3 V did not exceed 10 pA and was determined mainly by processes similar to the generation current of the p–n junction. Exposure of the samples to light radiation with λ up to 840 nm led only to a slight increase in the photocurrent in this range of V_b. When λ became less than 840 nm, which corresponds to the GaAs band gap, the reverse branches of the I–V_b characteristic began to exhibit an oscillating component with an amplitude proportional to the incident light intensity and a period independent of the λ, similarly to [1].

These oscillations were monotonically suppressed with increasing temperature and completely disappeared at $T \approx 100$ K. As can be seen from Fig. S1a, both the amplitude of the oscillations and the value of the background non-oscillating component of the photocurrent exhibit complex behavior with a change in λ. This is more clearly seen from Fig. S1b, which shows the dependences of the photocurrent values on λ at the maxima (stars) at $V_b = 109$ mV and minima (triangles) at $V_b = -5$ mV of the seventh oscillation for all measured curves. The seventh oscillation was chosen arbitrarily, but all other oscillations showed the same dependence. The general behavior of the photocurrent with a change in λ without taking into account the oscillating component is not unexpected and is consistent with early measurements of the photocurrent on such structures [2]. The dependence on λ of the oscillating component of the photocurrent, which is the subject of this article, will be considered later. In addition, it was found that the dependences of the photocurrent on the wavelength $I(\lambda)$, measured at $V_b = 109$ mV (red curve) and at $V_b = -5$ mV (blue curve), not only coincide well with the dependences at the minima (triangles) and maxima (stars), but also exhibit additional features at 806 and 684 nm, corresponding to the exciton peak and the appearance of light holes in the spectrum [2, 3].

It is important to note that, as can be seen from Fig. S1, the photocurrent at λ less than 650 nm begins to decrease sharply, reaching at $\lambda = 565$ nm to values of ~ 20 pA, which are at the sensitivity limit of our measuring equipment and does not allow measuring the ratio of the oscillating and non-oscillating components current, $I_{\rm osc}/I_{\rm non}$, in the shortwave range λ. Therefore, in what follows, measurements of the photocurrent from λ will be carried out and analyzed not at equal illumination intensity, but under conditions of maintaining the equality of non-oscillating components of the photocurrent in the voltage region where the oscillations disappear. This will allow us to reveal the value of the $I_{\rm osc}/I_{\rm non}$ ratios as accurately as possible, especially in the short-wavelength range, where otherwise their correct measurements are problematic. Moreover, this gives a greater clarity of the influence of λ on the $I_{\rm osc}/I_{\rm non}$ ratios and adds clarity to the interpretation of this effect considered below. Note that this approach to $I_{\rm osc}/I_{\rm non}$ measurements is correct due to the experimentally verified linear dependence of the photocurrent on the illumination intensity in the range of parameters that is relevant for us.

S2. Resonant tunneling through a wide quantum well in a magnetic field parallel to heterolayers. For additional verification, we also experimentally studied tunneling through a 60 nm rectangular well in n–i–n RTD structures similar to [4], which also showed a quadratic shift and suppression of resonance features in Bort $B_{\rm ort} \sim 2$ T (see Fig. S3), as in the case of our measurements of photocurrent oscillations.

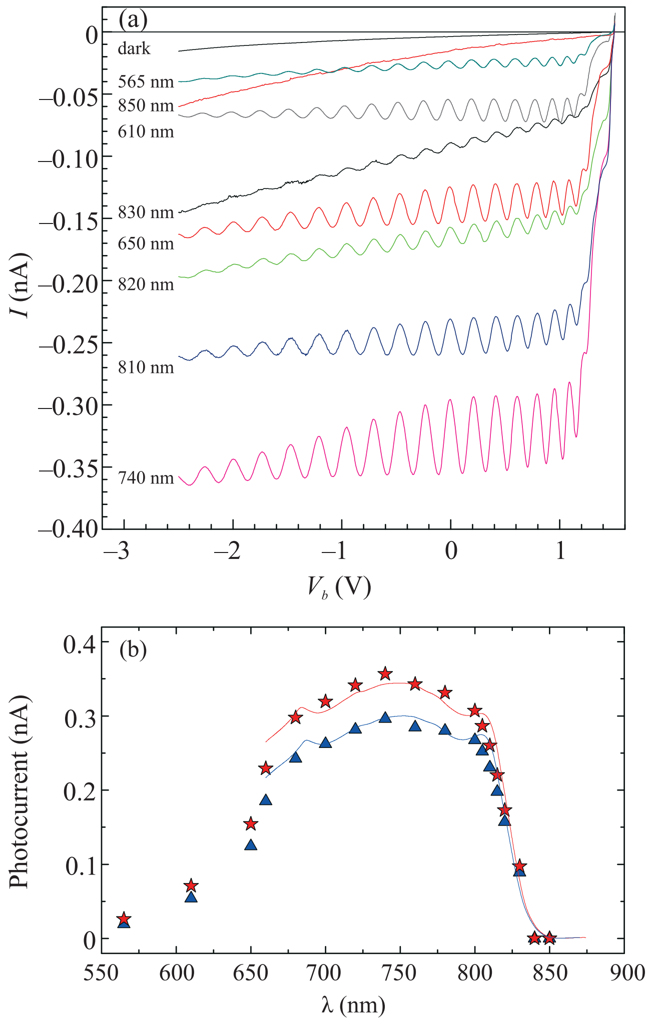

Fig. S1. (a) – The reverse branches of the $I-V_b$ characteristics at $V_b < 1.5\,\mathrm{V}$ under illumination with light at $P = 10^{-2}\,\mu\mathrm{W}$ with wavelengths in the range from 850 to 565 nm; (b) – The dependences of absolute values of photocurrent versus wavelength λ at the maxima oscillation (stars) at $V_b = 109\,\mathrm{mV}$ and minima oscillation (triangles) at $V_b = -5\,\mathrm{mV}$ for all $I(V_b)$ measured curves from Fig. S2a. Solid lines correspond to the $I(\lambda)$ dependences measured at $V_b = 109\,\mathrm{mV}$ (red curve) and at $V_b = -5\,\mathrm{mV}$ (blue curve)

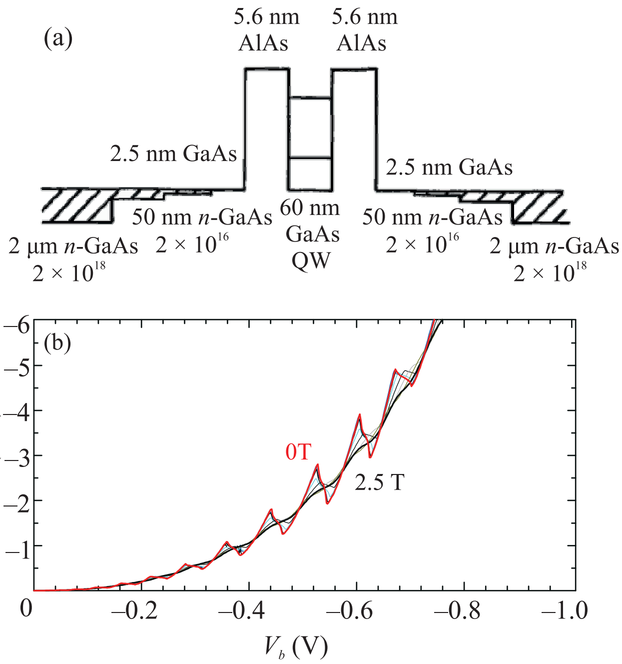

Fig. S2. (a) – Schematic energy-band diagram of a double barrier resonant tunneling structure with a quantum well; (b) – I–V_b curves in a magnetic field from up to 2.5 T with a step of 0.5 T

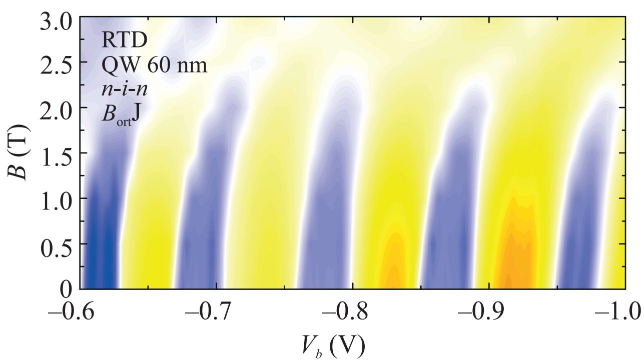

Fig. S3. Shift of tunneling resonances with increasing B in accordance with $e\Delta V_b = f(eB_{\rm ort}\Delta s)^2/2m^*$

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