Supporting Information for

Plasmonic Resonance Enhanced Low Dark Current and High-Speed InP/InGaAs Uni-Traveling-Carrier Photodiode

Bojian Zhang[1], *Yingjian Liu*[1], *Kai Jiang*[1], *Fangli Wang*[1], *Muyi Yang*[1], *Songpo Guo*[1] , *Zhengfu Han*[1,2] *and Liang Wang*[1,*]

[1]Department of Optics and Optical Engineering, University of Science and Technology of China, Hefei City, Anhui Province 230026, China.

[2]CAS Key Laboratory of Quantum Information, University of Science and Technology of China, Hefei City, Anhui Province 230026, China.

[*]*Corresponding Authors: lwang121@ustc.edu.cn*

Supplementary Note 1. Absorption of different incident light polarization angles at 1550 nm**.**

The absorption curve of different polarizations is shown in Supplementary Figure S1. We can see that the absorptions under different polarizations are all around 10.203%, with slight changes (variation <1%). Since the gap is large enough, the influence of a single nanodisk on adjacent nanodisks is negligible.

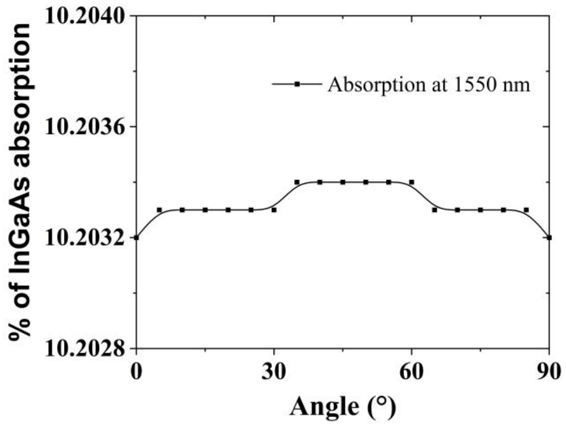

Figure S1. Absorption of different incident light polarization angles at 1550 nm.

Supplementary Note 2. Dark current of devices with different junction areas.

The dark current-voltage (I-V) curves of the photodiodes (with plasmonic structures) are shown in Supplementary Figure S2. The dark current value at -3V is 2.02 nA, 2.82 nA, 4.88nA for the devices with junction areas of 100 μm^2, 225 μm^2, 400 μm^2, respectively. In general, the dark current of the devices is larger while the junction areas are bigger. The dark current of all test devices at -3V bias is less than 10nA.

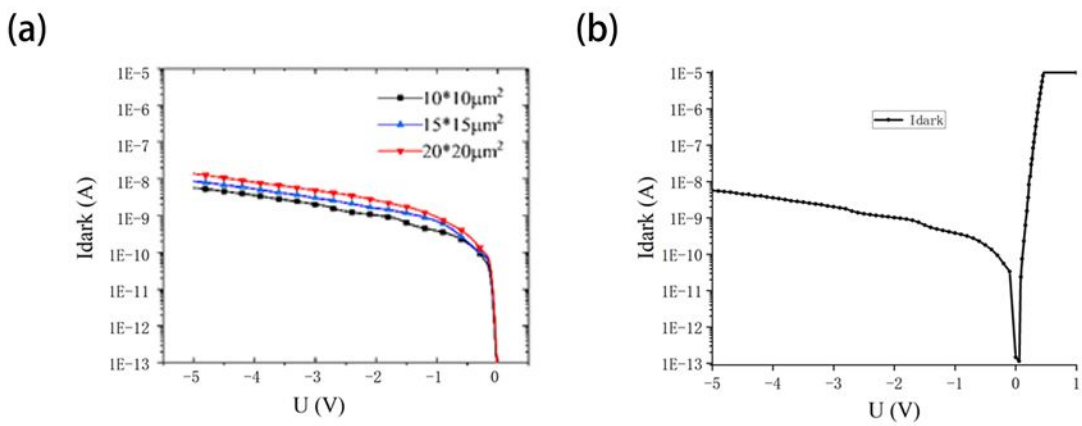

Figure S2. (a) Dark current characteristics for devices with different junction areas. (b) Dark current characteristics for devices (from -5V to 1V).

Supplementary Note 3. Plasmonic PD device with larger nanodisk radius and its characteristic I-V curve.

A device with a nanodisk array having the same junction area as the device of Figure 2 and a plasmonic structure with the same period (T=400 nm) and a larger radius R is shown in Supplementary Figure S3(a). The larger nanodisk radius leads to the plasmonic resonance peak red-shift. It can be seen that compared with the plasmonic photodiode with 130 nm radius, the absorption enhancement caused by plasmonic resonance is not obvious. The nanodisk array is characterized by SEM as shown in Supplementary Figure S3 (b), and the radius of a single nanodisk is about 130 nm. The I-V curve of this device is shown in Supplementary Figure S3 (c), its photocurrent is lower than that of the device with plasmonic structure shown in Figure 3 (a). This is because the larger R of the nanodisk causes the LSPR peak red-shifted, and the plasmonic resonance at 1550nm is not obvious.

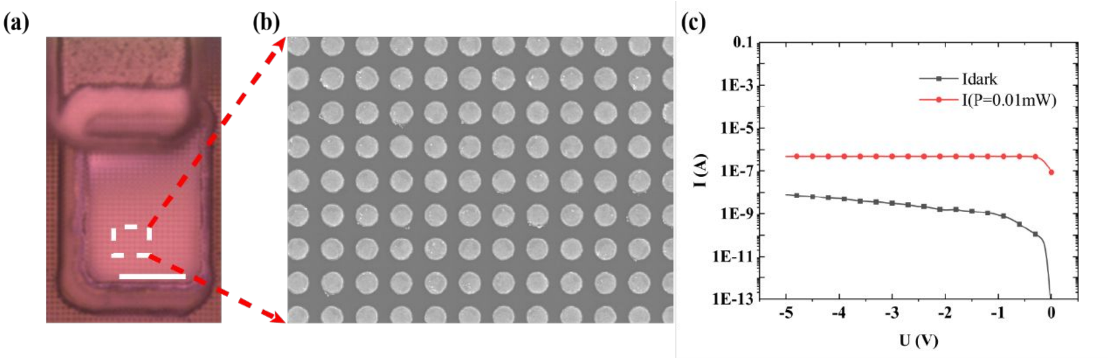

Figure S3. (a) UV optical image of an array of nanodisk and signal-contact on the UTC photodiode. The scale bar is 5 μm. (b) SEM image of an array of nanodisk antenna structures. The scale bar is 2 μm. (c) Dark current and photocurrent characteristics for the device.

Supplementary Note 4. Simulated response of a plasmonic UTC photodiode with a thinner absorption layer.

A model was established by FDTD to analyze the absorption distribution of plasmonic UTC photodiode with an absorption layer of only 30 nm. The material parameters of InGaAs in the model are taken from [1]. As shown in Supplementary Figure S4, the absorption of both the entire absorption layer and the top 10 nm under the influence of plasmonic resonance are analyzed. Due to the near-field enhancement characteristics of LSPR, the top 10 nm absorption in the absorption layer accounts for the main part.

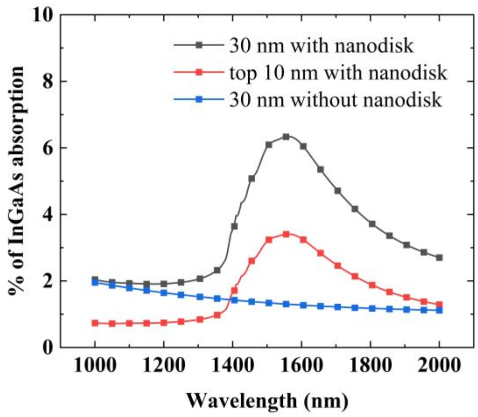

Figure S4. Calculated absorption of the plasmonic UTC device in InGaAs absorption layer, which absorption layer is 30 nm, when illuminated along the x-direction: black line is the total absorption of the 30nm absorption layer; red line is the absorption of the top 10 nm absorption layer; blue line is the absorption without plasmonic structure.

Supplementary Note 5. High-frequency computing model.

For a typical UTC device, its bandwidth is mainly determined by the travel time and the RC constant of the device. The travel time τ_A of the absorption layer can be expressed as [13]:

$$\tau_A = \frac{W_A^{\ 2}}{3D_e} + \frac{W_A}{\upsilon_{th}} \quad (1)$$

where W_A is the thickness of the absorption layer, D_e is the effective electron diffusion velocity, υ_{th} is the thermionic emission velocity ($2.5\times10^7 cm/s$ in InGaAs). The travel time τ_C of the absorption layer can be expressed as [13]:

$$\tau_C = \frac{W_C}{\upsilon_{os}} \quad (2)$$

where W_C is the thickness of the absorption layer, υ_{os} is the electron over-shoot velocity ($4\times10^7 cm/s$ in InP) which is faster than the saturation velocity. According to equations (1) and (2), it is easy to conclude that τ_A is dominated travel time when $W_A = W_C$. To increase the bandwidth of the UTC photodiode, it is important to reduce the thickness of W_A. The bandwidth design limit is when collection layer travel time τ_C becomes the dominant ($W_A \to 0$ or W_C ? W_A). At this limiting case, the bandwidth $f_{3dB,\tau}$ is simplified to $2.8/(2\pi\tau_C)$.

In this case, the bandwidth of the device is mainly limited by two parts: collection layer travel time and RC constant. The 3dB bandwidth of the device, the bandwidth generated by the collection layer travel time of the device, and the bandwidth generated by the RC of the device can be described as follows [13]:

$$f_{3dB} = \left(\sqrt{\frac{1}{f^2_{3dB,\tau}} + \frac{1}{f^2_{3dB,RC}}} \right)^{-1} \quad (3)$$

$$f_{3dB,\tau} = 2.8/(2\pi\tau_C) \propto 1/W_C \quad (4)$$

$$f_{3dB,RC} = 1/(2\pi RC) = 1/(2\pi(R_L + R_{\text{int}})\varepsilon A/w) \propto w/A \quad (5)$$

where A is the area of the junction, w is the thickness of the depletion layer (is approximately equal to W_C in this case). Equation (3) can be simplified as:

$$f_{3dB} = \frac{1}{2\pi\sqrt{(\tau_C/2.8)^2 + \tau_{RC}{}^2}} = \frac{2.8\upsilon_{OS}}{2\pi\sqrt{W_C{}^2 + (C/W_C)^2}} \quad (6)$$

where $C = 2.8(R_L + R_{\text{int}})\varepsilon A\upsilon_{OS}$. By observing Equation (6), it can be found that there is a maximum value for the bandwidth f_{3dB} of any value of C, when

$$W_C = \sqrt{C} \quad (7)$$

The parameter $R_L + R_{\text{int}}$ is selected as a constant ($R_L + R_{\text{int}} = 50\Omega$) for analysis.

Supplementary Note 6. Metallic losses.

Figure S5 shows the metallic losses of the plasmonic structures when the thickness of the absorber layer is 10 nm, 30 nm, and 120 nm, which are obtained by FDTD simulation. It can be seen that the metallic loss is about 8%, so the incident light is lost by 8% by the plasmonic structure and then interacts with the absorption layer. Combining with Figure 4, Figure 6 and Figure S5, it can be seen that even if the metal loss is about 8% and the metal loss tends to increase slightly with the thinner the absorber layer, the absorption enhancement factor of the plasmonic structure is higher when the absorber layer is thinner. However, the absorption value is still greatly influenced by the absorption coefficient of the absorption material.

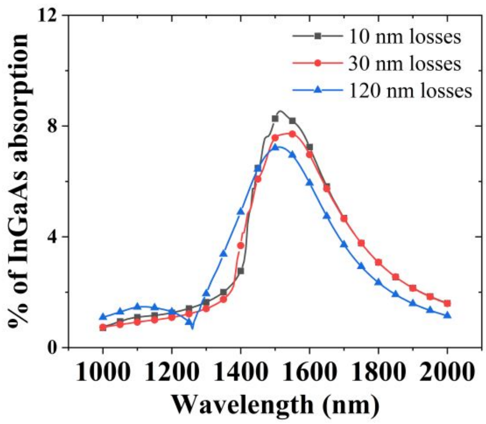

Figure S5. Metallic losses of plasmonic structures.