Plasticity of persistent photoconductance of amorphous LaAlO₃/SrTiO₃ interfaces under varying illumination conditions

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ABSTRACT: We report on transport measurements under optical stimulation of persistent photoconductance (PPC) at the interface between amorphous LaAlO₃ films and SrTiO₃ crystals. The spectral response in the visible was analyzed under varying illumination conditions and exposure times down to milliseconds. The PPC is plastically modulated by optical stimuli of varying strength and duration, demonstrating fine-tuned photoconductive responsivity over a diversity of cumulated timespans. Interestingly, under optimal conditions, the photoconductance is sensitive to intensity contrasts under conditions comparable to bright-sunlight environments. The prospects of exploiting photoconductance—including potential strategies to reach higher sensitivity—are discussed in the context of neuromorphic applications.

KEYWORDS: *Persistent photoconductance, oxide interfaces, neuromorphic engineering, photonics, two-dimensional electron systems*

It is known that a two-dimensional electron system (2DES) emerges at the $\text{LaAlO}_3/\text{SrTiO}_3$ (LAO/STO) interface, showing a variety of properties, including high electrical mobility¹, two-dimensional superconductivity² and strong Rashba spin-orbit fields³. The epitaxial LAO/STO heterostructure, where the mechanism for the generation of the metallic interface is driven by electrostatic boundary conditions⁴, has grabbed most of the attention. Interestingly, a 2DES can be also generated at the interface between amorphous LaAlO_3 (a-LAO) films and STO single crystals due to the creation of oxygen vacancies –which act as electron donors– under the reductive conditions during the growth^{5,6,7}. In spite of the different origins, similar transport properties are observed in both systems, e.g., the values of electron mobility are comparable for both epitaxial and a-LAO/STO interfaces⁸. This raises the interest in amorphous interfaces, as the sample preparation can be done at room temperature, enabling an easier integration into well-developed semiconductor technologies.

In this work, we analyze the properties of a-LAO/STO interfaces in relation to its persistent photoconductance (PPC)⁹. This is a phenomenon –observed in many other semiconductors and two-dimensional systems^{10,11}– whereby the conductance is increased after excitation with visible or ultraviolet light, so that the initial value prior to the photoexcitation is only fully recovered after prolonged periods of time^{12,13}. PPC has been studied in both epitaxial^{9,14,15,16} and amorphous interfaces¹⁷, and different physical mechanisms have been proposed for each type of interface, being oxygen vacancies suggested playing a fundamental role in a-LAO/STO interfaces. Among potential applications, a particularly interesting prospect for PPC is to exploit its modulation capability to emulate the plasticity of biological synapses using optical inputs as stimuli, as proposed for other materials^{18,19,20,21}. This would be of interest in photonic circuits where integrated light sources may be exploited to drive plastic photoresponses. Alternatively, artificial retinas²² would also benefit from incorporating plastic photoresponses.²³ In contrast to other neuromorphic developments, this particular application would require sensitivity to ambient illumination in visual scenes.

Here we focus our study to the a-LAO/STO interface to seek the sensitive threshold to varying illumination settings and find that, under optimal conditions this system is sensitive to contrasts approaching the peak of solar terrestrial irradiance. Although this threshold forbids the application in dynamic sensing of natural scenes, it could be of interest for other applications where this limitation is less severing, as in recognition of quasi-static visual patterns of large enough irradiance or as photoresponsive synaptic elements in integrated photonic systems, where non-natural light sources are used for optical stimulation. In this respect, the aforementioned simplicity of a-LAO/STO sample preparation can be an important asset for its integration into existent semiconductor technologies.

All things considered, this work is intended to explore the sensitivity of the PPC in a-LAO/STO to short pulses of light –down to millisecond timescales– under varying illumination conditions approaching terrestrial conditions of solar irradiance. The tunability of the conductance is also analyzed by measuring the cumulative effect of optical stimuli on the plastic PPC response. With this in mind, we contacted the interface between the amorphous LAO layer and the STO

substrate by Al wire bonding (Figure 1c). Amorphous layers with thickness $\sim 3 - 6$ nm were deposited at room temperature by pulsed laser deposition in an oxygen partial pressure $P_{O_2} = 10^{-4}$ mbar. The conductance was measured with injected currents typically in the range of $I \approx 1 \mu\text{A}$ for lower resistance devices ($R \lesssim 10^6 \Omega$) or $I \approx 1$ nA for higher resistance ($R > 10^6 \Omega$). The photoexcitation experiments were carried out at room temperature using lasers of different wavelengths in the visible –red ($\lambda = 638$ nm), green ($\lambda = 520$ nm), blue ($\lambda = 450$ nm) and violet ($\lambda = 405$ nm)–. Under direct illumination conditions (figure 1a), the laser beam was steered via a mirror directly towards the sample, illuminating an area of size $\sim 1 \text{ cm}^2$ and the irradiance on the sample was varied in a range of values down to $P_w \approx 2.5 \text{ W}\cdot\text{nm}^{-1}\cdot\text{m}^{-2}$ (see also the Supporting Information Notes S1 and S2 for details regarding the measurement of P_w). This value is relatively close to the peak of solar spectral irradiance in the visible at ground level ($\approx 1.4 - 1.6 \text{ W}\cdot\text{nm}^{-1}\cdot\text{m}^{-2}$ for green light)²⁴. Alternatively, high focusing through a high-numerical-aperture objective was also performed in some experiments (Figure 1b).

We first discuss the impact on the photoconductance of the change in transport properties over time, which is known to occur in a-LAO/STO interfaces²⁵. The origin of these changes can be traced back to the refilling of oxygen vacancies by dissociation of O_2 molecules from the environment, resulting in a continuous and gradual decrease of conductance over long periods²⁵. As expected, the same phenomenon is also present in our samples, as confirmed by monitoring the resistance over a timescale spanning up to $\Delta t \approx 2 \times 10^7$ s (≈ 8 months) after the time of growth. The results, plotted in Figure 2a, show that the resistance –measured in darkness– goes from an initial value $R \approx 6 \times 10^4 \Omega$ up to $R \approx 8 \times 10^8 \Omega$ about eight months later, exhibiting a highly nonlinear dependence on the time elapsed from growth (aging time in Figure 2a). Importantly, these effects influence the photoconductance, which also changes due to aging. To see this, we measured the relative change of conductance with illumination quantified as $\frac{\delta\sigma_{ph}(\tau_{il})}{\sigma_0} = \frac{\sigma_{ph}(\tau_{il}) - \sigma_0}{\sigma_0}$, where σ_0 is the initial conductance and $\sigma_{ph}(\tau_{il})$ denotes the conductance measured immediately after being illuminated through a time τ_{il} (illumination time). Figure 2a plots the values of $\frac{\delta\sigma_{ph}(\tau_{il}=10 \text{ s})}{\sigma_0}$ measured with irradiance $P_w \approx 10^3 \text{ W}\cdot\text{nm}^{-1}\cdot\text{m}^{-2}$ at different wavelengths and aging times $\lesssim 2 \times 10^7$ s. The inspection of this Figure reveals a remarkable enhancement of $\frac{\delta\sigma_{ph}(\tau_{il})}{\sigma_0}$ with strong nonlinear dependence on the aging time (see also Figure 2b). We stress that the strong increase of the relative conductance is due to the large decrease with aging of the initial conductance σ_0 . This observation is born out in Figure 2c, where the absolute changes of conductance, i.e., not normalized to the initial value σ_0 , are shown. Clearly, with increased resistance the absolute changes are much smaller than for fresher samples with lower resistance. Nevertheless, as discussed below, in spite of the much smaller value of $\delta\sigma_{ph}(\tau_{il})$, the rapid growth of the normalized photoconductance $\frac{\delta\sigma_{ph}(\tau_{il})}{\sigma_0}$ is correlated with an increased sensitivity to illumination contrast of optical stimuli, which is beneficial for applications aimed at sensing visual inputs. Accordingly, in the ensuing discussion we will refer to $\frac{\delta\sigma_{ph}(\tau_{il})}{\sigma_0}$ rather than $\delta\sigma_{ph}(\tau_{il})$.

At this point it is important to observe that the phenomenon of persistent photoconductance has been observed in a wide range of semiconductors, where it is widely accepted to be caused by DX-centers^{12,13}. Briefly, DX-centers are defect states due to, e.g., interstitials or vacancies, that induce donor states that are coupled to the lattice. Changes in the occupancy of such states induced by light may cause large lattice relaxations in the lattice around the defects. Thus, when one electron leaves behind the defect state, the structural relaxation prevents the return of the carrier to the initial state after photoexcitation, causing the persistent change in conductance. Note that the decrease of the absolute value of photoconductance observed in high-resistance samples ($\delta\sigma_{ph}(\tau_{il})$ in Figure 2c) is compatible with the identification of oxygen-related vacancies as DX-centers. More specifically, a reduction of vacancies due to aging should cause a decrease of active DX-centers, so that the absolute change of conductance would be smaller, as observed in the experiments (Figure 2c).

Before proceeding, we note that a control of the aging process is needed to reach a stable state, preventing further evolution of the transport properties with time. Interestingly, a possible strategy towards this objective may be provided by the observation that the deposition of an additional a-LAO film grown at a O_2 pressure higher than that used for the first a-LAO layer reduces the aging process by orders of magnitude²⁵, which could be a promising route to achieve the required stability. Importantly, growth conditions –e.g., oxygen pressure or the thickness of the amorphous layer– can be used to control the resistance state of the sample (Supplementary Note S4).

Now we address the potential for neuromorphic applications, which requires a functional response that emulates the plasticity of biological synapses.²⁶ To analyze this aspect, we measured $\frac{\delta\sigma_{ph}(\tau_{il})}{\sigma_0}$ after impinging the samples with trains of light pulses of irradiance $P_w \approx (150 - 1000)$ $W \cdot nm^{-1} \cdot m^{-2}$, defined by the number of pulses ($N_p = 1 - 10$) and the width of every single pulse $W_p \approx 0.5, 1, 5$ ms (Figure 3b). In this case, the illumination time is defined as the cumulated time resulting from all light pulses, i.e., $\tau_{il} = N_p \times W_p$. Since we need to quantify the plasticity of the PPC response, we define an additional parameter, the *probe time* τ_{pr} at which the photoconductance $\delta\sigma_{ph}(\tau_{il})/\sigma_0$ is measured after switching the light off. Both the illumination (τ_{il}) and probe (τ_{pr}) times are defined in Figure 3a, which displays data from measurements of the photoconductance in response to selected pulse trains. The latter are visualized in the lower panel as the intensity detected from light reflected off the surface, while the main panel of Figure 3a displays the photoconductance measured after photoexcitation. From this Figure we clearly see that: (i) after photoexcitation with short pulses ($\tau_{il} < 200$ ms) the conductance is not recovered to the initial state over periods extending several tens of seconds, and (ii) the value of the persistent conductance measured at different probe times ($\tau_{pr} < 70$ s in Figure 3a) increases with the illumination time τ_{il} , hinting at the plastic character of the photoconductive response.

To have a complete picture of the plastic response, we extended these results to all wavelengths and a wide range of illumination times. Accounting for the number of pulses and

their individual width, the ensemble of our measurements covered cumulated illumination times that spanned over almost three orders of magnitude ($\tau_{il} \approx 2.5 - 1000$ ms). The results of this extensive study are summarized in Figure 3c, which plots the values of the photoconductance $\delta\sigma_{ph}(\tau_{il})/\sigma_0$ measured at different probe times ($\tau_{pr} = 0$ s, i.e., immediately after switching the light off and at $\tau_{pr} = 15, 30$ and 45 s). The outcome of this study reveals that the photoconductance $\delta\sigma_{ph}(\tau_{il})/\sigma_0$ can be modulated over two decades for the cumulated illumination timespan $\tau_{il} \approx 2.5 - 1000$ ms (Figure 3c). Therefore, the data shown in Figure 3 demonstrates that the cumulated illumination time in pulse trains can be used to fine-tune the plastic PPC response in the a-LAO/STO system.

Now, can this fine-tunability be used under conditions approaching ambient illumination environments? To gauge this possibility, we have to tackle the responsiveness of the system to illumination conditions that imply low enough irradiance ($P_w \ll 10^2 \text{ W}\cdot\text{nm}^{-1}\cdot\text{m}^{-2}$, see Figure 4c). In this context it is relevant to quantify the noise level and estimate the sensitivity threshold for a detectable change in conductance. For that purpose, we measured the photoconductive signal after photoexcitation with irradiance $P_w < 10^2 \text{ W}\cdot\text{nm}^{-1}\cdot\text{m}^{-2}$ and illumination time $\tau_{il} = 1500$ ms – see Figure 4a for data acquired in a sample about 10^6 s after its growth, when its resistance was $R \approx 8 \times 10^5 \Omega$ (see Figure 2a)–. The results show that the photoconductance is larger at short wavelengths, i.e., $\delta\sigma_{ph}/\sigma_0 > 15\%$ at $\lambda = 405$ nm, while $\delta\sigma_{ph}/\sigma_0 \approx 1\%$ at $\lambda = 638$ nm, see Figure 4a. It is also observed that the photoconductance is not increasing linearly with irradiance, and it appears to show a sudden increase at a threshold value that for blue-violet light is $P_w \lesssim 6 \text{ W}\cdot\text{nm}^{-1}\cdot\text{m}^{-2}$ (Figure 4a). To evaluate the noise amplitude, we measured the conductance in darkness for periods of several tens of seconds (Figure 4b). We see that the random fluctuations in conductance give rise to noise amplitude $\delta\sigma_n/\sigma_0 \approx 0.4\%$, as calculated from the root mean square value over the analyzed time interval. This value has to be compared with the amplitude of the photoconductance $\delta\sigma_{ph}/\sigma_0 \approx (0.4 - 900) \%$ under illumination time $\tau_{il} = 1500$ ms for a sample of aging time 2×10^7 s (Figure 4c).

We compared the observed noise amplitude with the noise due to thermal motion of electrons in conducting media. The spectral density of thermal noise is given by²⁷

$$G_v(f) = \left(\frac{2Rh|f|}{\exp(h|f|/k_B T) - 1} \right) \approx 2Rk_B T \quad (\text{Equation 1})$$

where f is the frequency, R the resistance, T the temperature and h and k_B are the Planck and Boltzmann constants, respectively. The right hand of Equation 1 is valid for frequencies $|f| \ll \frac{k_B T}{h}$, which is fulfilled at room temperature up to $f \approx 10^{12}$ Hz, well above the bandwidth of conventional electrical instrumentation. The spectral density $p_{rnd}(f)$ was calculated via discrete-time Fourier transform as

$$p_{rnd}(f) = \frac{1}{Lf_s} \left| \sum_{n=0}^{L-1} v_L(n) e^{-j2\pi n f / f_s} \right|^2 \quad (\text{Equation 2})$$

for a signal $v_L(n)$, corresponding to a finite number of L voltage readings and f_s is the sampling frequency ($f_s = 2$ Hz in our measurements). The spectral density calculated from Equation 2 is displayed in Figure 4b, yielding a value $p_{rnd}(f) \approx -45$ dB/Hz. The spectral density of thermal noise associated with the resistance $R \approx 8 \times 10^8 \Omega$ calculated from Equation 1 is $G_v \approx -99$ dB/Hz, see Figure 4b. Therefore, for the highest resistance state –which, as discussed above, has the largest sensitivity to photoconductance– the spectral density of the random signals measured with the used instrumentation (described in the Supplementary Note S3) is considerably larger than the intrinsic thermal noise of the device resistance (Figure 4b, right panel). This is an important observation towards optimizing the signal-to-noise ratio. Indeed, we show that the use of lock-in amplifiers for voltage detection –using phase-sensitive detection to single out signals at specific frequencies– results in noise amplitude much closer to the theoretical estimation for thermal noise (see the Supplementary Note S3).

We address now the sensitivity of photoconductance to different illumination conditions. The discussion is focused on data extracted from experiments carried out with resistance $R \approx 8 \times 10^8 \Omega$ after photoexcitation with illumination time $\tau_{il} = 1500$ ms and varying illuminance conditions spanning a broad range $P_w \approx 2.5 - 15000$ W·nm⁻¹·m⁻². This range of illuminance can be translated into a range of photon arrival rates A_r that, for the case of green light ($\lambda = 520$ nm), is equivalent to $A_r \approx 6.6 \times 10^{18} - 3.95 \times 10^{22}$ photons/s/m²/nm. To put these values in context, we note that photon arrival times in the visible can be estimated for different habitat illuminance conditions from references in the literature, such as light from sky in a bright midday sun on land ($A_r \approx 10^{18} - 10^{19}$ photons/s/m²/nm), brightness of a computer monitor ($A_r \approx 10^{16} - 10^{17}$ photons/s/m²/nm), brightness from natural scenes ($A_r \approx 10^{15} - 10^{16}$ photons/s/m²/nm), light from sky in a dull-day ($A_r \approx 10^{15}$ photons/s/m²/nm) or mid-dusk on land ($A_r \approx 10^{13} - 10^{14}$ photons/s/m²/nm), while the damage to the eye happens above $A_r \approx 10^{21}$ photons/s/m²/nm^{26,28}. These different illumination environments are indicated across the range of arrival photon rates shown in Figure 4c.

To evaluate the responsiveness of the photoconductance of the a-LAO/STO interface to a diversity of environmental conditions, the values of $\delta\sigma_{ph}(\tau_{il})/\sigma_0$ were measured at different wavelengths under illumination time $\tau_{il} = 1500$ ms (Figure 4c). The data reported in this Figure was acquired immediately after switching off light ($\tau_{pr} = 0$ s). Empty symbols correspond to direct illumination, while solid symbols represent the data acquired under focusing conditions. For the latter, the value of the illuminance is determined at the back aperture of the objective lens. The data displayed in Figure 4c shows that high-NA focusing increases substantially the sensitivity to varying illumination conditions (Figure 4d). This is not unexpected since the strong reduction of the spot size is overcompensated by the strong increase of photon flux over the reduced illuminated area, resulting in larger changes of conductance. We also observe that the photoconductive response is highly nonlinear with wavelength, with values that go from

$\delta\sigma_{ph}(\tau_{il})/\sigma_0 \approx (0.3 - 30)\%$ for red to $\delta\sigma_{ph}(\tau_{il})/\sigma_0 \approx (3 - 900)\%$ for violet. Interestingly, the data displayed in the low irradiance region demonstrate that the photoconductance of the amorphous LAO/STO system is sensitive to changes in brightness comparable to bright day conditions ($A_r \approx 10^{18} - 10^{19}$ photons/s/m²/nm). Attempts to measure the photoconductance for lower rates, i.e., $A_r < 10^{18}$ photons/s/m²/nm, give values that are too low to be detected above the noise level (Figure 4c). This is partly accounted for by the sheer drop of photoconductance that occurs for irradiance below $P_w \lesssim 6 \text{ W}\cdot\text{nm}^{-1}\cdot\text{m}^{-2}$, especially noticeable for blue and violet, which limits the sensitivity at the low end of irradiance. Further studies are needed to understand this observation.

Summing up, our research gives a perspective on the use of persistent photoconductance of the amorphous LAO/STO interface for neuromorphic applications. As a general rule, we find that highly-resistive states are desirable to improve the signal-to-noise ratio. This, in turn, may require finding appropriate conditions for materials preparation, especially regarding the stability of the transport properties and oxygen stoichiometry, which is discussed in the text. Also, our study reveals that sensitivity to visual contrasts in bright day conditions is feasible with a-LAO/STO, albeit the sensitivity required for scenes under more demanding conditions, such as dull-day or dusk ambient light, is far more challenging and calls for other approaches to increase the responsiveness. This sensitivity threshold is certainly a limitation for applications demanding dynamical sensing of visual scenes, but it could afford an alternative for image acquisition and recognition of visual patterns of large enough intensity. Another interesting aspect is that measurements of photoconductance carried out at the lowest irradiance conditions were done after relatively long illumination times ($\tau_{il} = 1500 \text{ ms}$), roughly one order of magnitude above the timescales typical for perceptual cognition ($\sim 100 \text{ ms}$)²⁶. One possible way to improve the performance may be with the help of plasmonics. Indeed, the same principles that enable plasmonics to improve absorption in photovoltaic devices and solar cells²⁹ or to boost surface-enhanced Raman spectroscopy³⁰ may serve well the purpose to increase the photoconductance sensitivity to lower photon arrival rates. Further studies are required to explore this possibility.

■ ASSOCIATED CONTENT

Supporting Information.

Experimental details, transport characterization under controlled illumination conditions, determination of the illuminance, noise analysis

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Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This work was supported by the Spanish Ministerio de Ciencia, Innovación y Universidades through Grants No. MAT2017-85232-R (AEI/FEDER,UEEU), and Severo Ochoa SEV-2015-0496, and the Generalitat de Catalunya through Grant No. 2017 301 SGR1377. We acknowledge collaboration and discussions with Dr. Florencio Sánchez regarding thin film growth. Y. C. acknowledges the China Scholarship Council grant nº 201506890029. This work is part of the PhD Thesis of Y.C.

Figure 1. (a) Sketch of the experimental setup used to measure the photoconductance of a-LAO/STO under direct illumination. Appropriate instrumentation is used to generate short pulses of light of different wavelengths (violet, blue, green, red). The polarizer is used to vary the illumination on the sample. The voltage is measured under illumination. The intensity of reflected light is measured by a photodetector. (b) In some experiments, the photoconductance is also measured by illuminating the sample through a high-numerical-aperture lens. The CCD camera is used to locate the beam spot on the sample, while a CMOS detector is used to adjust the focus location along the out-of-plane direction. (c) Cross-sectional view of the amorphous LAO/STO interface.

Figure 2. (a) Resistance measured in darkness (black circles) at different times elapsed from the deposition of the amorphous LAO layer (up to roughly eight months). The figure also includes the photoconductance $\frac{\delta\sigma_{\text{ph}}(\tau_{\text{il}})}{\sigma_0}$ measured at different wavelengths under illumination time $\tau_{\text{il}} = 10$ s. The steady nonlinear increase of resistance and photoconductance is related to the aging of the amorphous LAO/STO interface, plausibly due to refilling of oxygen vacancies by dissociation of O_2 molecules from the environment. (b) Time dependence of the conductance under illumination of irradiance $P_w \approx 10^3 \text{ W}\cdot\text{nm}^{-1}\cdot\text{m}^{-2}$ and different wavelengths. A, B and C refer to different aging times indicated in panel (a). The strong nonlinear increase of photoconductance caused by aging is shown in these figures. The insets display a zoom of the photoconductance at aging time A. (c) Plot of the absolute changes of conductance ($\delta\sigma_{\text{ph}}(\tau_{\text{il}})$) corresponding to the data in (b).

Figure 3. (a) Photoconductive response of the amorphous LAO/STO interface under illumination time $\tau_{il} = 25 - 200$ ms with violet light ($\lambda = 405$ nm) and irradiance $P_w \approx 10^3 \text{ W} \cdot \text{nm}^{-1} \cdot \text{m}^{-2}$. The lower graph displays the detected intensity (arbitrary units) of light reflected from the sample during the illumination with the light pulses. The illumination time is defined by $\tau_{il} = N_p \times W_p$, where N_p is the number of pulses and W_p the width of every individual pulse ($W_p \approx 5$ ms in the data shown in this panel). The figure also indicates different probe times τ_{pr} where the photoconductance is measured, which are used in data presented in panel (c). (b) The upper panel displays the detected intensity of light reflected from the sample after illumination with pulse trains defined by $N_p = 1 - 10$ and $W_p \approx 0.5 - 5$ ms, resulting in illumination times spanning the interval $\tau_{il} = 2.5 - 1000$ ms. The lower graph displays the time evolution of photoconductance corresponding to the response to every particular pulse train. (c) Photoconductance measured at different probe times ($\tau_{pr} = 0, 15, 30$ and 45 s) as a function of the illumination time.

Figure 4. (a) Photoconductance measured under low irradiance ($P_w < 10^2 \text{ W}\cdot\text{nm}^{-1}\cdot\text{m}^{-2}$) at different wavelengths (from top to bottom: red, green, blue, violet) and illumination time $\tau_{il} = 10 \text{ s}$. (b) *Left*: Conductance measured in darkness over an interval of a few tens of seconds, displaying random noise, where $\delta\sigma$ refers to deviations of conductance with respect to the average σ_0 . *Right*: power spectral density (PSD) of the measured noise calculated from Equation 2 and spectral density of thermal noise calculated from Equation 1 are shown in blue and red line, respectively. (c) Photoconductance measured after illumination time $\tau_{il} = 1500 \text{ ms}$ and probe time $\tau_{pr} = 0 \text{ s}$ as a function of the photon arrival rate calculated for green light. Numbers in this Figure denote regimes of photon arrival rates for different environmental conditions: (1) light from sky in a dull-day ($A_r \approx 10^{15} \text{ photons/s/m}^2/\text{nm}$); (2) natural scenes ($A_r \approx 10^{15} - 10^{16} \text{ photons/s/m}^2/\text{nm}$); (3) brightness of computer monitors ($A_r \approx 10^{16} - 10^{17} \text{ photons/s/m}^2/\text{nm}$); (4) bright midday sun on land; (5) damage to the eye ($A_r \gtrsim 10^{21} \text{ photons/s/m}^2/\text{nm}$). These estimations are extracted from the literature ^{26,28}. For illustrative purposes, the random noise shown at the bottom of the Figure was generated by the MATLAB function *rand()* with the same amplitude as the one obtained from experiments. (d) Photoconductance measured under direct illumination with different irradiance values (upper graph) or under high-numerical-aperture focusing (lower graph).

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