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Taming photons to sense fast and faint infrared signals

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The performance of infrared photodiodes designed with narrow-bandgap semiconductors is limited by inherent noise and the need for a low-temperature operation to mitigate it, while they also face a speed–efficiency trade-off.

Invisible to the human eye, infrared (IR) photons play a crucial role in communication, imaging, remote sensing, spectroscopy, autonomous driving, healthcare and other applications[1]. Semiconductor photodiodes capable of detecting IR photons have a narrow bandgap, meaning they need less energy to excite an electron from the valence to the conduction band. Consequently, thermally excited electrons at room temperature can easily cross this energy gap, causing a high dark current in photodiodes, even in the absence of light. This increased dark current generates extra noise, obscuring signals and reducing the signal-to-noise ratio (SNR) — an important measure of signal clarity against background noise. While lower temperatures can reduce noise, they also make detectors more expensive and less portable.

The capacity to detect weak IR signals is just one aspect of the requirements for contemporary systems. Today's systems often necessitate fast photodiodes capable of capturing ultrafast processes while maintaining sensitivity to extremely faint signals, which may consist of only a few or even a single photon[2]. Based on modern fabrication techniques, high-speed IR detectors need thin photo-absorption regions to reduce the distance electrons and holes travel between electrodes. However, thin detectors can only partially absorb incoming photons, resulting in decreased efficiency, similar to how sheer curtains partially block light. This incongruity leads to the well-known trade-off in developing a detector that is both fast and efficient.

Now, writing in *Nature Photonics*, Chen and colleagues introduce a thin infrared avalanche photodiode (APD) that demonstrates ultrafast response, high efficiency, high gain and record-low noise[3]. The researchers employed a compound semiconductor, AlInAsSb, to design the APD, integrating a thinner-than-usual photo-absorption layer to capture a significant portion of incoming IR photons. AlInAsSb, a quaternary alloy comprising aluminium, indium, arsenic and antimony, is utilized in IR detectors for its capacity to detect a broad range of IR wavelengths, such as 2 µm. This thin photo-absorption layer enables high-speed operations and substantially reduces dark current, a common problem with narrow-bandgap absorbers. Although a fast response and low dark current are crucial, high detection efficiency is essential for capturing faint signals and improving the SNR. However, a thin photo-absorber layer in a fast photodiode leads to low quantum efficiency and negatively impacts the SNR.

So, how can we achieve high detection efficiency while increasing speed and reducing dark currents in the IR detectors? Chen and

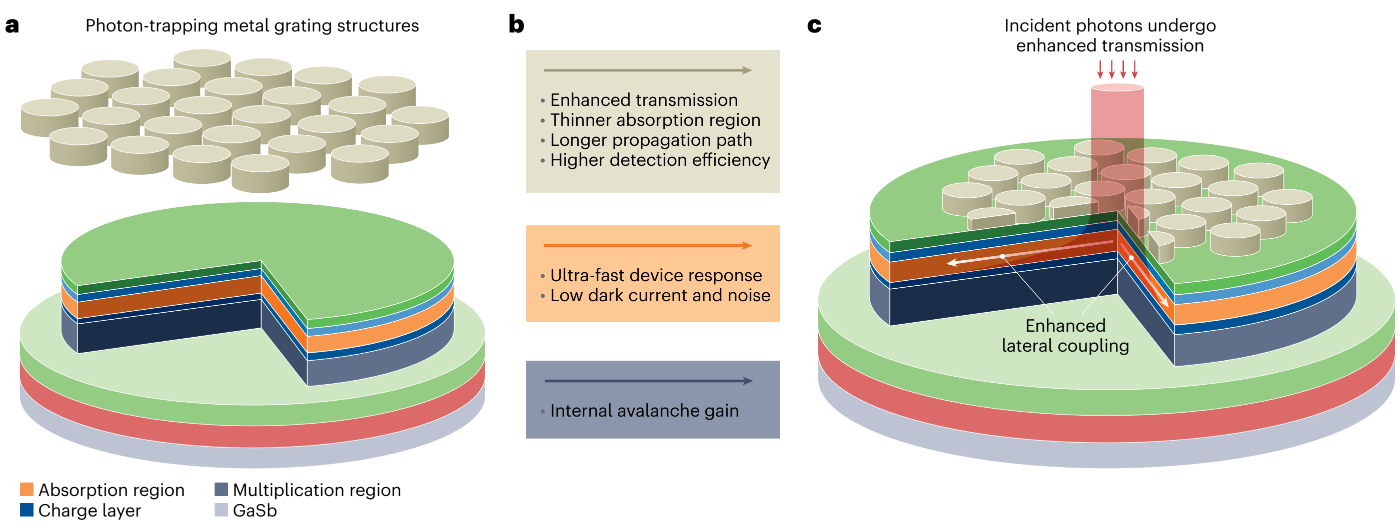

Fig. 1 | Schematics showing different components of an APD designed with photon-trapping structures. a, Metal grating structures and the cross-section of the APD with a separate thin absorption region sitting on top of a charge layer and a multiplication region. **b**, Several benefits are listed for photon-trapping structures that use a thin photo-absorption region to reduce the noise without compromising the detector efficiency when integrated on an innovative APD. **c**, Incident photons scattered into lateral modes allow a much higher proportion of photons to be absorbed in the active region, as the lateral extent of a fast APD photodiode is many times the thickness of the absorption region.

colleagues employed photon-trapping metal grating structures on the photodiode surface, achieving high quantum efficiency even with a thin IR photo-absorber layer (Fig. 1a). Photon-trapping surface structures on silicon were recently shown to overcome the trade-off between high speed and high efficiency in p–i–n photodiodes — where an intrinsic semiconductor layer is situated between heavily doped p-type and n-type layers[4] — and APDs[5]. These structures bend incident light beams by almost ninety degrees into laterally propagating modes of light along the horizontal plane of the substrate in photodiodes (Fig. 1c). This increases the propagation length of light, allowing for longer interaction with absorbing materials and enhancing light absorption efficiency. Highly efficient photodiodes can be engineered even with an extremely thin absorption layer by optimizing photon-trapping structures' size, shape and periodicity.

Chen and colleagues demonstrated a parallel approach to enhancing absorption efficiency using plasmonic photon-trapping structures based on metal grating arrays. These structures enhance photon transmission and transform propagating electromagnetic waves into laterally oriented evanescent waves with a significantly increased local density of states, confined within a minimal depth of a thin semiconductor film. As in conventional photodiodes, most photons remain undetected in a thin semiconductor film without such photon-trapping structures. The team used an extremely thin light absorber and detected a large fraction of the incident photons, overcoming the trade-off between speed and sensitivity in their photodiodes.

When photon-trapping surface structures are shaped like holes, they reduce device capacitance by decreasing the total surface area. This results in increased device bandwidth (due to lower resistor-capacity time or RC time) and reduced noise, thanks to a smaller material absorber volume[4,5]. Using metal-based plasmonic photon-trapping structures, rather than creating holes, is an attractive solution for narrow-bandgap semiconductors. Creating light-trapping holes on the device surface can significantly increase the absorber's surface area, potentially causing material damage during fabrication. This can drastically increase the surface leakage dark current, especially for infrared APDs with narrow-bandgap materials exposed to high electric fields. An effective passivation layer can address this issue.

While most photodiodes create one electron-hole count from a single photon, APDs can amplify the electron-hole pairs by many folds, making weak signals easily discernible. An APD also amplifies any thermally excited unintended dark current generated in the photodiodes, contributing to further amplified dark currents. In IR APDs, achieving high SNR can be challenging when dark current isn't effectively suppressed, particularly when handling weak or faint signals common in many emerging applications. Compared with a similar APD reported by the same group with a 2-μm-thick absorption region that needed cryogenic temperatures to suppress the dark current and gain acceptable SNR, this photon-trapping APD with one-tenth thickness can operate close to room temperature while exhibiting better sensitivity[6]. At the same time, the thin absorption layer in the APDs reduced the dark current by over two orders of magnitude compared with previously reported counterparts. Thus, the combination of lower dark current and high detector sensitivity in photon-trapping APDs substantially improved the SNR by over 70-fold. Moreover, there is an impressive, >4-fold improvement in the gain-bandwidth product compared with current state-of-the-art alternatives. This design elevated the operating temperature to 180 K, almost 50 degrees higher than existing counterparts.

Metal gratings have some limitations, as their efficiency and resonance frequency depend on the metal type, the size and shape of the metallic nanostructures, and the surrounding dielectric environment. Consequently, these detectors often display wavelength selectivity and perform best at certain wavelengths. However, by meticulously designing the plasmonic structures, the detectors can be optimized for specific wavelength ranges, making them well-suited for particular applications.

Infrared technology is revolutionizing various fields by offering eye-safe, low-loss fibre optic and free-space optical communication systems. In free-space optical systems, IR light minimizes atmospheric absorption, scattering and turbulence effects and is expected to play a significant role in future 6G networks. Light detection and ranging (LiDAR) systems and biomedical imaging are just a few emerging areas that use IR technologies.

To unlock the full potential of these cutting-edge systems, innovators need to develop new methods to modulate infrared light at higher frequencies and detect increasingly shorter pulses of light containing only a few photons. With ongoing advancements such as Chen and colleagues' work, the future of infrared technology promises to be transformative and integral to numerous industries. The development of ultrafast, highly efficient, high-internal-gain and low-noise photodetectors may pave the way for many communication, imaging and sensing application breakthroughs.

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Competing interests

The author declares no competing interests.