A single photon detector inspired by the human eye

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An infrared single photon detector that provides high amplification and ultra-low noise levels may spur advances in telecommunications, imaging, and medical instrumentation.

Many applications like medical instruments, imaging systems, and telecommunications devices require high speed and high signal-to-noise ratios, but photodetector sensitivity often limits their performance. To overcome this obstacle, researchers have increasingly focused on creating devices sensitive enough to detect a single photon. Despite significant progress, creating single photon detectors (SPDs) for the shortwave infrared spectrum has proven particularly challenging. Since the energy of a photon in the infrared spectrum is very small—less than $10^{-18}$ J—reliably detecting this energy requires very low noise levels.

Currently, the best semiconductor technologies for SPDs are avalanche photodetectors (APDs) and superconducting-SPDs (SSPDs). These devices provide reliable and robust operation with a small footprint. However, these technologies suffer from serious limitations in the shortwave infrared spectrum. APDs provide only limited amplification to boost the signal levels beyond electronic noise. Their inherent noise levels rapidly increase as the gain is increased, and they require high voltages to operate. In contrast, SSPDs can perform single photon detection with low noise levels, but require extremely low temperatures, usually less than 10 K. In addition, their light capturing cross-section is small, reducing their overall quantum efficiency.

At the Bio-inspired Sensors and Optoelectronics Lab (BISOL) at Northwestern University, we have developed a novel approach to this problem that draws upon biological methods of single photon detection. Many vision systems in nature use SPDs, including the human eye: see Figure 1(a). The eye is a powerful detector that can see color in bright light and grayscale in almost total darkness. Specialized cells called rod cells, shown in Figure 1(b), make this low light vision possible.

Three properties of rod cells significantly influenced our design. First, rod cells are rich in a photosensitive molecule called rhodopsin, which ensures the successful capture of light. Second, activated rhodopsin triggers a cascade of events that alter ion flow. Na$^+$-K$^+$ Pump: sodium potassium pump.

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Figure 3. Gain and dark current as a function of voltage for the 30µm FOCUS detector. Gains approach 10,000, while voltage never exceeds 1.5 V. $P_{\text{opt}}$: optical power.

the state of nanoscale ion pumps. Finally, the change in ion pumps significantly alters the ion flow and leads to an amplified signal.

We created and fabricated an SPD called FOCUS (focalizing carrier augmented sensor)\(^4\) that couples a large absorption region with a nanoscale sensor. Figure 2 shows a schematic diagram of the SPD. Like the rod cell, our FOCUS detector has a large absorption region for improved quantum efficiency. Photons generate electron-hole pairs in the absorption region. Carriers are then attracted towards nanoscale pillars that sense, control, and amplify the current flow.

Figure 2 shows gain as a function of voltage for the 30µm version of FOCUS detectors. The devices demonstrate very high signal amplification with optical gain values reaching 10,000, even at room temperature. In contrast to APDs, which require up to 100V to operate, the FOCUS detectors require less than 1.5V (or the voltage of a single AA battery). The detector noise level is also below the expected electronic shot noise. In addition to high-gain devices, we have developed FOCUS detectors with several gigahertz bandwidths. These detectors have ultra-low jitter to account for the timing of specific photon-based events.

Thus, the FOCUS detector is an important advance in infrared single photon detection. Its high gain, low noise, and low jitter make it superior to existing short-wave infrared SPDs. This single photon detector may drive development in many fields, including biophotonics, optical tomography, nondestructive materials inspection, homeland security, infrared vision, quantum imaging, and cryptography.

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Hooman Mohseni joined the Northwestern University faculty in 2004. Before that he was a technology leader for several government, domestic, and international projects at Sarnoff Corporation. His main research interests are bio-inspired sensors and systems, novel optoelectronic devices, advanced nanofabrications, nanophotonics, and plasmonic devices.

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References


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