correspondence

Exaggerated sensitivity in photodetectors with internal gain

To the Editor — A growing number of reports on photodetection with low-dimensional materials have assumed that a photodetector with a high responsivity has a high sensitivity[1–7]. This misinterpretation stems from an incorrect calculation of the device noise in the presence of internal gain. Given the prevalence and significance of this mischaracterization, we believe it is imperative to promote the use of the appropriate noise formula to ensure the consistency and practical utility of the relevant literature.

Low-dimensional materials are an important frontier for novel photodetectors, and large internal gains have enabled the demonstration of high responsivities[8]. The current responsivity, defined as the photocurrent per optical power incident on the detector, is an indication of the internal gain of a detector. While internal gain is important to amplify the signal above the noise floor of the read-out electronics[9], modest gains of 10^2 to 10^3 are sufficient to render the read-out noise inconsequential in most modern read-out electronics. In this regime, the detector is often shot noise-limited, implying that a further increase in gain will not yield any improvement in the device sensitivity, as we will show. Indeed, detector designs that simply maximize responsivity often result in low device speed or high dark current, both of which are actually detrimental to performance.

The misperception stems from an incorrect shot noise formula that fails to account for the increase in noise power in the presence of internal gain[10,11]. In addition, the primary metrics for device sensitivity, the noise-equivalent power (NEP) and the specific detectivity (D^*), depend on the device noise and are therefore affected by any incorrect estimation of noise. In the presence of an internal gain, β, the shot noise arising from a current I is[10–12]:

$$I_\mathrm{n} = \sqrt{2qF\beta I\mathrm{BW}}$$

where BW is the 3 dB bandwidth of the device, and F the Fano factor, which we here assume to be unity for the sake of brevity. Assuming a Poissonian photon flux incident on the detector with an average N_ph photons per measurement, the signal-to-noise ratio is $\mathrm{SNR_{in}} = \sqrt{N_\mathrm{ph}}$. When the detector is limited by shot noise, the SNR at the detector output is simply the ratio of the signal photocurrent to the shot noise current, I_n: here, the gain contribution cancels out, yielding a maximum SNR (for unity quantum efficiency) $\mathrm{SNR_{out}} = \sqrt{N_\mathrm{ph}} = \mathrm{SNR_{in}}$. However, using the incorrect expression for the shot noise ($I_{\mathrm{n}_0} = \sqrt{2qI\mathrm{BW}}$) leads to a fictitious improvement of the SNR by a factor of $\sqrt{\beta}$ with respect to the SNR at the input of the detector. This impossible improvement of SNR leads to a negative noise figure, which is thermodynamically infeasible[13,14].

This common misinterpretation and improper use of the shot noise formula has led to several unrealistic sensitivity claims[1–7,15]. Since the magnitude of the error increases for larger gain, this is of particular relevance for photodetectors with very large internal gain. As an example, a device with a gain of $\beta = 10^4$ will see a fictitious enhancement of two orders of magnitude (that is, $\sqrt{\beta}$) in SNR when using the incorrect noise expression, as well as an equally fictitious improvement in its NEP and D^*.

We believe that a proper understanding of the effects of internal gain on photodetector performance will facilitate realistically optimized designs where other important parameters such as the detector speed are not sacrificed. ❐

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Competing interests

The authors declare no competing interests.