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Physical frontiers in infrared photo-detectors

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Presented by Guy Laval

In order to enlighten the State of the Art presented in this Issue, as well as to sketch directions of research for performance enhancements, we briefly derive the main physical concepts which are at stake in infrared detectors. We stress the point that only *intrinsic* (or *basic*) limitations are considered so that this discussion leaves apart very important aspects such as:

- noise due to pixel non-uniformities,
- $1/f$ noise due to materials quality,
- noise due to read-out circuitry,
- bandwith limitations,
- etc.

Two main groups of infrared detectors exist, which are based on very different physical effects: *quantum devices* and *thermal devices* [1,2].

In *quantum infrared detectors*, photons induce optical transition between quantum states. The detection scheme is based on the fact that electrons are mobile on the excited state while not on the fundamental state (see Fig. 1(a)). In this detection scheme, the signal i_s is given by $i_s = RP_{\text{inc}}$, where P_{inc} is the incident power to be detected. R is the responsivity of the device $R = \eta q/h\nu$ (in $\text{A} \cdot \text{W}^{-1}$): basically, it tells how many electrons η are created by one photon. The current noise is classically given by $i_n = \sqrt{quAJ_d\Delta\nu}$, where q is the electron charge, A is the device area and $\Delta\nu$ is the bandwidth of the measurements. u is a parameter dependent on the type of transport scheme (4 for photoconduction, 2 for photovoltaic, ...) the value of which is not far from unity. Finally J_d is the dark current density flowing through the structure in absence of a signal. The minimum detectable signal *NEP* (noise equivalent power) is the incidence power for which the S/N ratio is one, i.e.,

$$NEP = \frac{\sqrt{quAJ_d\Delta\nu}}{R}. \tag{1}$$

From this latter quantity, it is easy to derive the minimum temperature contrast that can be resolved by the detector. This *noise equivalent temperature difference NETD* is given by the change in temperature which leads to a signal-to-noise ration of 1, i.e.:

$$NETD = \frac{NEP}{\frac{\mathrm{d}}{\mathrm{d}T}\int_{\Delta\lambda}\frac{\mathrm{d}\Re}{\mathrm{d}\lambda}\mathrm{d}\lambda}, \tag{2}$$

where $\mathrm{d}\Re/\mathrm{d}\lambda$ is the blackbody emittance and $\Delta\lambda$ is the spectral acceptance of the detector. Clearly, these quantities are not intrinsic, depending on bandwidth and detector area. In order to derive a quantity able to compare infrared detector technologies, a quantity called *detectivity* has been introduced, given by $D^* = \sqrt{A\Delta\nu}/NEP$. For quantum detectors, the detectivity is thus given by:

$$D^* = \frac{R}{\sqrt{uq(J_L + J_B)}}, \tag{3}$$

Moreover, the dark current $J_d = J_L + J_B$ has two origins:

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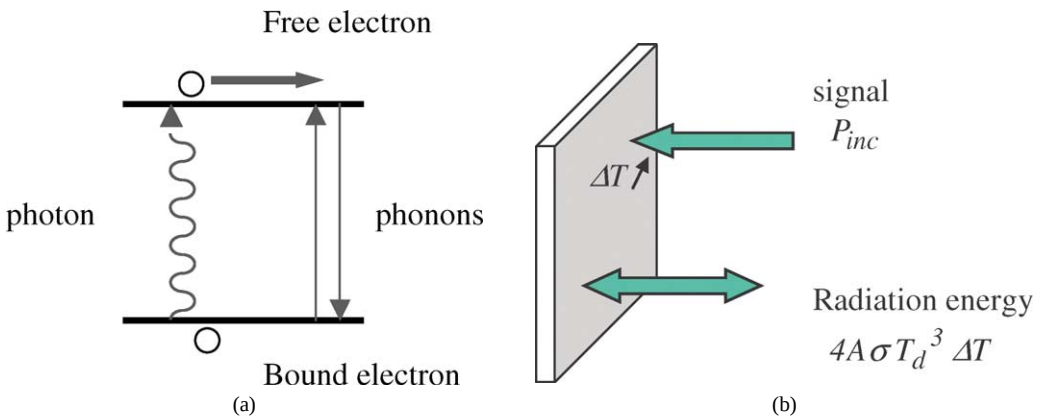

Fig. 1. Schematic principles of quantum versus thermal infrared detectors. (a) Quantum detector, (b) thermal detector.

- The fact that optical transitions are by-passed by purely thermal transitions between the quantum states. Clearly, this dark current (*leakage current*) is thermally activated $J_L = J_0\,\mathrm{e}^{-h\nu/kT_d}$ with an activation energy given by the photon energy $h\nu$ (at most), where k is Boltzmann's constant and T_d is the detector temperature. J_0 may be viewed as related to the trial frequency of thermal transitions per unit area G_{th} (i.e., $J_0 = qG_{th}$) and $\mathrm{e}^{-h\nu/kT_d}$ as the rate of success of these thermal transitions. By the quantum micro-reversibility principle, this thermal generation rate G_{th} is equal to the recombination or capture rate R_{th}.
- The current J_B due to the blackbody radiation of the environment, given by Plank's law.

Much wisdom is gained from Eq. (3). Firstly, the higher the detectivity at a given wavelength, the better the technology, which pinpoints the importance of the detectivity as a figure of merit. Then, clearly, it is desirable to get rid of the spurious leakage current by decreasing the detector temperature T_d. However, below a given temperature, the leakage current drops below the blackbody current, $J_L(T_d) \leqslant J_B$ so that there is no gain in decreasing the detector temperature. Below this limit, the detector is said to be in the *Background Limited Infrared Performance* (BLIP) regime. Above the *BLIP temperature* given by $J_L\ (T_{BLIP}) = J_B$, the performance of the device decreases. Clearly, for practical reasons, the higher the BLIP temperature, the better the device. The maximum detectivity obtainable with ideal quantum devices, given by:

$$D^* = \frac{R}{\sqrt{uqJ_B}} = \frac{\lambda_0}{hc}\frac{1}{[2\pi uc\int_0^{\lambda_0}(1/\lambda^4)(1/(\mathrm{e}^{hc/\lambda kT}-1))\,\mathrm{d}\lambda]^{1/2}} \tag{4}$$

is shown in Fig. 2, together with performances obtained with devices which will be described in this Issue. Fig. 2 demonstrates that, in most of the available quantum technologies and for most of the spectral range, experimental detectivities are close to the theoretical limits.

In quantum detectors, basic progress is then mostly expected in the enhancement of BLIP temperatures given, at best, by:

$$kT_{BLIP} = \frac{h\nu}{\log(qG_{th}/J_B)}. \tag{5}$$

Evidently, the thermal generation-recombination rate G_{th} plays the major role in the BLIP temperature enhancement. Different schemes are developed today to engineer this rate:

- Enhancing the crystal qualities and doping schemes [3];
- Decreasing the detecting volume by enhancing the materials-photon interaction in a micro-cavity [4] or using grating resonances [5];
- Decreasing the electron-phonon interaction by using phonon bottleneck effects in quantum boxes [6];
- Decreasing the Auger recombination effect by band gap engineering [4].

One has to note that, to our best knowledge, no upper limit to T_{BLIP} values as a function of detected wavelength, based on fundamental physical considerations, has been demonstrated to this day, which leaves room for further research in the quantum detection field. Very basic research is beginning in different places, trying, for instance, to engineer the phonon density of states in MEMs, to use optical parametric effects, ...

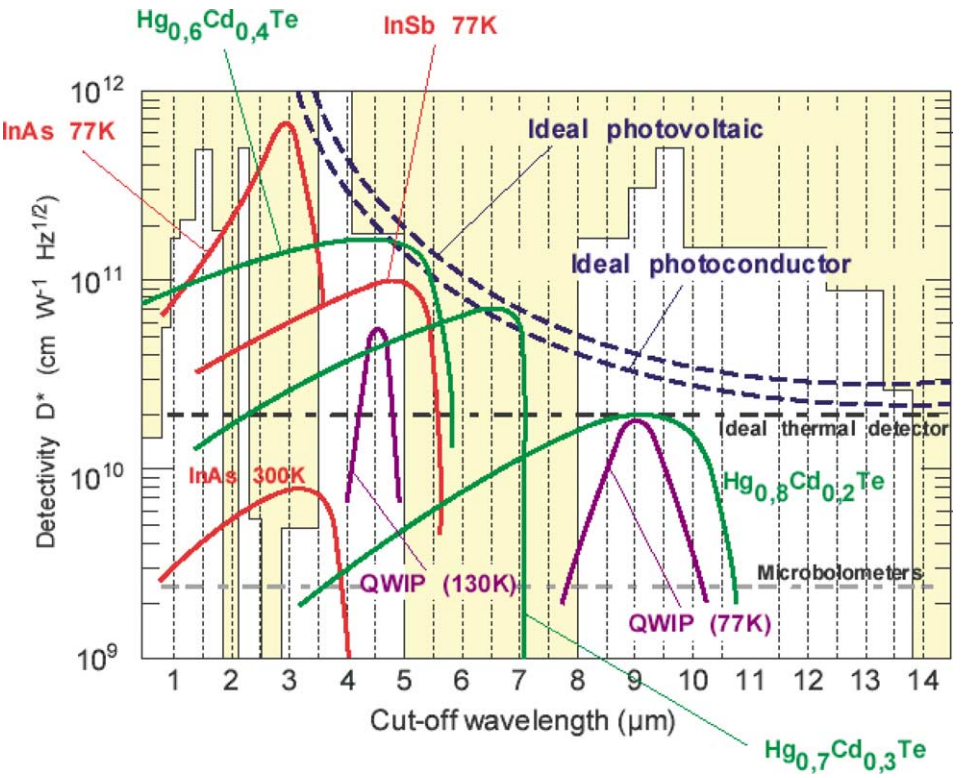

Fig. 2. Comparison between the detectivities of different infrared detector technologies. The background temperature is 300 K, the angle of view is 2π steradian.

In a *thermal detector*, the light flux is transformed into heat by absorption (see Fig. 1(b)). Now, *at most*, the absorbed signal power is $P_s = P_{\text{inc}}$ leading to a temperature increase ΔT given by:

$$P_{\text{inc}} = H\frac{\mathrm{d}}{\mathrm{d}t}\Delta T + G\Delta T, \tag{6}$$

where H is the thermal mass and G is the thermal conductance of the device. Steady state is obtained after a typical time lag of $\tau = H/G$ and yields a maximum temperature enhancement of $\Delta T_{\max} = SP_{\text{inc}} = P_{\text{inc}}/G$ where S is the sensitivity of the device. Of course, all the technological know-how consists in transforming as much signal into heat, using thermal insulation to prevent leakage, ..., and in transforming the heat into a measurable current or voltage using bolometers with optimized materials, pyroelectric layers, ... Clearly, optimum design is a complex trade-off between a useable time constant τ (of the order of 10 s of ms) and a high sensitivity S. Impressive (even revolutionary) progress has been performed in these technologies, thanks to the microtechnology appraisal, which will be described in J.L. Tissot's paper in this issue [7]. *At steady state*, the absorbed power is dissipated as thermal radiation, following Stefan's law, leading to an temperature increase ΔT_s of:

$$\Delta T_s = \frac{P_{\text{inc}}}{4A\sigma T_d^3} = \frac{P_{\text{inc}}}{G_R}, \tag{7}$$

where σ is Stefan–Plank constant, A the detector area, T_d the detector working temperature and G_R is the radiation component of the thermal conductance of the detector. For a thermal detector, there is a temperature fluctuation given by the fluctuation–dissipation theorem:

$$\left\langle \Delta T_B^2 \right\rangle = \frac{4kT_d^2}{G_R}\Delta\nu. \tag{8}$$

Following the same arguments than above, we easily derive the detectivity limit of thermal detectors:

$$D^* = \frac{1}{4\sqrt{k\sigma T_d^5}}. \tag{9}$$

The detectivity of a thermal detector depends thus only on the detector temperature. Fig. 2 compares the theoretical detectivity of thermal detectors versus ideal quantum detectors. One has to note that, contrary to quantum devices, the detectivity of *practical* thermal devices depends *exponentially* on the surface since heat is better stored in a large device than in a small one, where heat leaks by the edges. However, we will not address this question since we are concerned with fundamental limitations.

From Fig. 2, one clearly sees that, in the 8 to 15 μm range, *ideal* room temperature operated thermal detectors would display performances very comparable with the one of cryogenically cooled quantum detectors. This explains the strong impetus to develop thermal detector arrays, particularly since the appraisal of micro-technology which allows complex micro-system to be implemented in large arrays.

Much information can be gained from Fig. 2. On the one hand, as already noted, there is now little room for improvement of basic quantum detector performances. Progress lies in high yields and higher uniformities (which favors QWIPs), a higher working temperature (if possible accessible to Peltier cooling), new functions (multi- and hyper-spectral, gating, skimming, ...) and better read-out silicon circuitry. On the other hand, it seems there are still important improvements to be expected from uncooled thermal detectors, through the use of new bolometric materials with higher thermal coefficients (i.e., higher thermal mass H), better thermal insulation techniques, ...

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