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Study on the thermal imaging application of quantum cascade detectors

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HIGHLIGHTS

- A 2D mechanical scanning imaging system was constructed based on a 9.3 μm QCD.
- The Noise Equivalent Temperature Difference for this imaging system is about 102.6 mK.
- Thermal images of an electric soldering iron and a projection lamp are obtained.
- Our research provides a proof-of-concept demonstration of IR imaging with QCDs.

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ABSTRACT

A 2D mechanical scanning setup was constructed, and was used to evaluate the potential of quantum cascade detector (QCD) for IR imaging. The peak responsivity of the studied QCD is 22.3 mA/W at 9.3 μm, and the Noise Equivalent Power (NEP) reaches $6.7 \times 10^{-10}\ \mathrm{W}/\sqrt{\mathrm{Hz}}$ at temperature of 82 K. The Noise Equivalent Temperature Difference (NETD) for this imaging system is estimated to be 102.6 mK. With this experimental setup, thermal images of an operating electric soldering iron and a projection lamp at about 310 K are obtained. The image of the projection lamp demonstrates the feasibility of human body imaging with this QCD. Our research provides a proof-of-concept demonstration of thermal imaging with QCDs and displays that QCDs are potentially useful for thermal imaging applications.

1. Introduction

High-performance photodetectors and thermal imagers operating in the infrared (IR) wavelength range (3–10 μm) have attracted great interest due to their wide applications in security surveillance, chemical sensing, and industrial process monitoring [1]. To the present, mercury–cadmium–telluride (MCT) and quantum well infrared photodetetctor (QWIP) are arguably the most established technologies for high performance infrared imaging applications. However, typified by substrate, lattice, surface, and interface instabilities, MCTs suffer from large (>20%) spatial non-uniformity, and a non-linear responsivity for thermal imaging application [2,3]. In addition, the manufacture of large MCT Focal Plane Arrays (FPAs) is exceedingly expensive due to the spatial uniformity, epitaxial difficulties, and low fabrication yields [4,5]. In contrast, quantum well infrared photodetectors (QWIPs) show excellent infrared detection and FPA imaging performance. Yet QWIPs also have a major limitation: non-negligible dark current resulting from the applied bias can easily saturates the readout capacitance in large-area FPAs and thus reduces the integration time [6]. Therefore, the operation temperatures of these photodetectors are limited by the dark current. This problem is more prominent at higher operating temperatures, and for this reason, the operation temperature of QWIPs has to be low enough, which limits their widespread use. It is therefore critical to develop novel detectors that enable material uniformity and low dark current for FPA imaging application.

As an alternative solution, quantum cascade detectors (QCDs), a type of photovoltaic QWIPs, operating without bias have been developed [6]. Such design could be advantageous, particularly for high operating temperatures [7,8] and many room temperature operation devices have been reported [9–11]. QCDs generate an electronic displacement through a cascade of quantum levels when the device is illuminated [6]. A typical QCD cascade period is composed of an "active region" dedicated to absorption and another part optimized for the electron's transfer from one period to another. Owing to the absorption of an IR photon, an electron is excited from the fundamental level of the structure to the excited state. It is then transferred into the ground level of the next period's active well by a carefully designed extraction cascade, which is adapted to the longitudinal optical (LO) phonon energy. This transfer of electrons induces a voltage drop between the two adjacent periods. The last period of the cascade structure is identical to the first one, and thus a significant photocurrent without applying any bias is expected by closing the circuit.

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With no dark current, QCDs are largely free from the limit of the integration time due to capacitance saturation of the read-out circuit, which is of great significance for generating high quality images in thermal imaging application [11]. Their thermal load is strongly reduced, which is of interest if the available cooling is limited, for example, in space borne systems. In addition, with the advantages of intersubband transitions in III–V materials, QCDs enable innate spectral selectivity, low background noise, radiation hardness, high speed operation and exceptional material uniformity, reproducibility, and yield, over a large area [7,8]. Therefore, QCD is a very promising alternative technology for FPA thermal imaging applications.

To the present time, QCDs have covered a large wavelength range from the near-infrared to the terahertz region [12–17]. Some performances, such as R_0A and detectivity, have achieved the same order of magnitude as MCTs and QWIPs within the corresponding detection wavelength region [7,18]. The performance of QCDs in thermal imaging application has been estimated theoretically. From all these analyses, higher working temperature and longer integration time are expected [7,19]. However there has no experimental report on QCDs thermal imaging.

In this work, we demonstrate a thermal imaging system using a quantum cascade detector (QCD) with peak wavelength of 9.3 μm. The system is based on mechanical scanning mechanism and the feasibility of application of QCDs in thermal imaging is studied. The Noise Equivalent Power (NEP) of the used QCD is measured to be $6.7 \times 10^{-10}\ \mathrm{W}/\sqrt{\mathrm{Hz}}$ at 82 K. For this system, a Noise Equivalent Temperature Difference (NETD) value of 102.6 mK is obtained. Images of an operating electric soldering iron and a projection lamp at about 310 K are demonstrated.

2. QCD thermal imaging system

2.1. Quantum cascade detector

The QCD in our experimental setup is a GaAs/AlGaAs multiple quantum well structure grown by molecular beam epitaxy, which consists of 50 periods of the active region embedded between two n-doped GaAs contact layers. A similar structure has been demonstrated in Ref. [20] in detail. The finished devices have square-shaped mesas of size $200 \times 200\ \mu\mathrm{m}^2$ and 45° multipass wedges fabrication.

The peak response wavelength of the detector is 9.3 μm with a peak wavelength responsivity of 22.3 mA/W at 82 K, as shown in Fig. 1. The QCD has a somewhat weaker responsivity compared with QWIPs and MCTs, but also a low dark current and a low noise. This low dark current allows longer integration time without saturating the read-out circuit capacity. For applications where longer integration time is possible, this characteristic can be exploited. With a calibrated blackbody as source, the Noise Equivalent Power (NEP) is measured to be $6.7 \times 10^{-10}\ \mathrm{W}/\sqrt{\mathrm{Hz}}$ at temperature of 82 K for this used device. This value is not so satisfactory and it can be largely due to the non-optimum single device. Optimized designs will induce higher performances for single devices and FPA application [20,21].

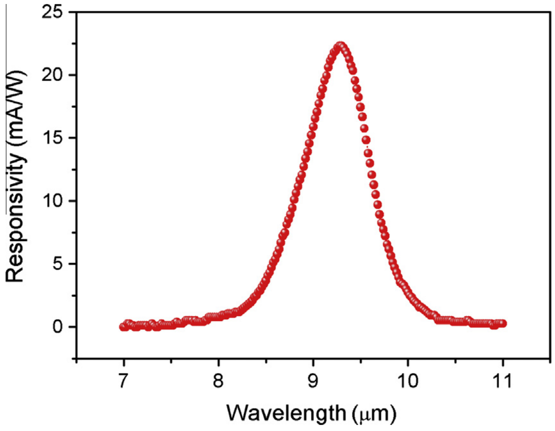

Fig. 1. Photocurrent response spectrum for the QCD at temperature of 82 K.

2.2. Experimental technique

A schematic of the experimental setup is shown in Fig. 2. The QCD operating at 82 K, is fixed on a copper heat sink and then mounted onto the cold finger of a liquid nitrogen cryostat. The cryostat is then placed on a computer controlled X–Y translation stage. The scanning plane of the QCD is ensured to be the focal plane (X–Y plane) of a $\mathrm{CaF_2}$ optical lens with a focal length of 40 mm.

The radiated infrared light from the sample is collected by the lens and then modulated by a chopper. The sample is thus imaged onto the scanning plane. The signal current generated by the detector at different positions is extracted as a voltage by a low noise current preamplifier. The amplified voltage is then read out by a lock-in amplifier (LIA) controlled by a computer for synchronization with the X–Y translation stage. Dealing with the voltage data at different positions, thermal images are obtained.

3. Experimental results

3.1. The Noise Equivalent Temperature Difference

The Noise Equivalent Temperature Difference (NETD) is one of the key parameters for infrared thermal imagers. We have examined this parameter of our system through calculating the System Intensity Transfer Function (SITF). The SITF represents the functional relation between input signal and output signal for a detector, which is typically linear relation [22]. The input signal is defined as the effective temperature difference between the target and the background at the infrared imaging system entrance window and the output signal as the response voltage of the detector in the test philosophy of SITF [23].

For an infrared thermal imager, a linear system can produce an output voltage difference that is proportional to the radiant exitance difference between a target and its background. Assuming a Lambertian collimated blackbody source, the response voltage difference can be given by

$$\Delta V = G\int_{\lambda_1}^{\lambda_2} R(\lambda)\,\frac{\Delta M_e\,\overline{T_{\mathrm{atm}}}\,\overline{T_{\mathrm{sys}}}\,\overline{T_{\mathrm{col}}}A_d}{4F^2}\,d\lambda, \tag{1}$$

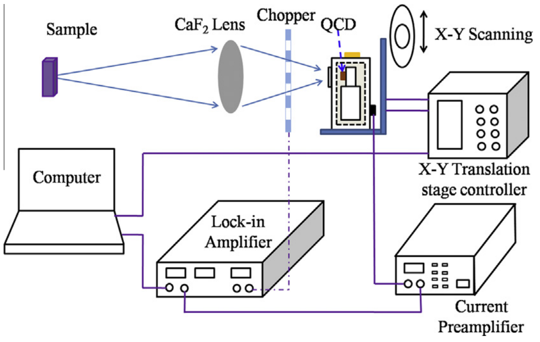

Fig. 2. Schematic of the thermal imaging experimental setup with a QCD.