Attojoule energy resolution of direct detector based on hot electron bolometer

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Abstract. We characterize superconducting antenna-coupled NbN hot-electron bolometer (HEB) for direct detection of THz radiation operating at a temperature of 9.0 K. At signal frequency of 2.5 THz, the measured value of the optical noise equivalent power is $2.0 \times 10^{-13}$ W·Hz$^{-0.5}$. The estimated value of the energy resolution is about 1.5 aJ. This value was confirmed in the experiment with pulsed 1.55-µm laser employed as a radiation source. The directly measured detector energy resolution is 2 aJ. The obtained risetime of pulses from the detector is 130 ps. This value was determined by the properties of the RF line. These characteristics make our detector a device-of-choice for a number of practical applications associated with detection of short THz pulses.

1. Introduction
Terahertz (THz) frequency range is quite attractive for a number of important practical applications, such as security systems [1] and medicine [2]. Unfortunately, employing of THz radiation in real practical applications associates with a number of difficulties related to the CW sources of THz radiation such as quantum-cascade lasers, gas-discharge lasers, frequency multipliers based on semiconductor superlattices and others. These sources are complex and not quite stable in operation in comparison with the pulsed sources.

For this reason, the design of devices based on effective methods of generating pulsed THz radiation is the most promising way of further development in this area. The optical rectification [3] and deference-frequency generation in nonlinear optical crystals [4] are among these methods. Pulsed THz sources are more reliable, so they are good candidates for using in the practical THz systems. At the same time, these systems require fast and sensitive detectors of THz radiation. That would provide for obtaining THz pulses without distortion of their characteristics.

Both features are combined in a direct detector based on the HEB that demonstrates a relatively good sensitivity with a short response time and operates at convenient liquid-helium temperatures. The HEB sensitive element is integrated with the logarithmic-spiral antenna for better coupling of the input radiation [5]. The measured value of the optical noise equivalent power of the superconducting NbN HEB direct detector is $2.0 \times 10^{-13}$ W·Hz$^{-0.5}$ at 2.5 THz [6]. The time constant can be calculated from the measurements of the HEB gain bandwidth established at the critical temperature [7]. The corresponding value is about 50 ps. The calculated value of the energy resolution is about 1.5 aJ.
This value was confirmed in additional experiment. In this paper, we report on the direct measurements of the HEB energy resolution at 1.55-µm wavelength. The obtained value of the energy resolution is also consistent with the THz range, because of the frequency independence of detector response in a wide range.

2. Device and setup
The HEB detectors were made from NbN films with thickness of about 4 nm on quartz substrates. We used both side polished substrates with roughness much less that the thickness of the NbN layer. Typical value of the sheet resistance was about 500 Ω. The critical temperature was about 9 K. The NbN deposition was followed by the in situ deposition of a 30 nm Au layer. Another Au layer on top formed a contact pads. The detectors were fabricated using DC magnetron sputtering, ion milling, lift-off patterning, and ion and chemical etching techniques. More details about the fabrication process one can find elsewhere [5].

The calculated value of the critical current density at 4.2 K was about 5·10^6 A·cm^2. The detector length-to-width ratio was 0.1 for better rf matching between the bolometer and the 50 Ω of employed coplanar line. Figure 1 shows the optical and atomic-force microscope (AFM) images of the bolometer sensitive element. In order to obtain the AFM photos, the upper dielectric SiO_2 layer was removed using the chemical etching, and thus the quartz substrate was also partially etched during this process.

![Figure 1. Photos of the central path of the bolometer: a – obtained from the optical microscope, b – obtained from the atomic-force microscope, c – the profile of the bolometer sensitive element along the direction marked with the yellow arrow.](image)

Figure 2 shows the schematic of the experimental setup. Pulsed 1.55-µm laser with pulse duration of less than 50 ps and repetition rate of 10 MHz was employed as a radiation source. The HEB was wire-bonded to a microstrip transmission line, and connected to a dc bias source, and low-noise amplifier (LNA) via the broadband bias-tee. The LNA gain was about 30 dB through the bandwidth of 0.2-4 GHz. The whole HEB arrangement was placed on special holder on a deepstick and maintained at the temperature close to the temperature of liquid-helium.
Figure 2. The schematic representation of the experimental setup. PL – 1.55-µm laser with pulse duration of less than 50 ps, OF – optical fiber, VOA – variable optical attenuator, BS – beam splitter, OPM – optical power meter, B – bias source, BT – bias-tee, LAN – low-noise amplifier with the bandwidth of 0.2-4.0 GHz, RTA – room-temperature amplifier with a bandwidth of 0.7-18.0 GHz, DO – digital oscilloscope with the upper frequency limit of 4.0 GHz.

A signal from LNA was transmitted to the room-temperature amplifier with the gain of 24 dB across the bandwidth of 0.7-18 GHz. The amplified signal was measured via the digital oscilloscope with the upper cut-off frequency of 4 GHz. We used the optical fiber to couple the input power to the bolometer. The power adjustment of the incident radiation was carried out using the optical tuneable attenuator. The laser beam was divided into two optical fibers, one of which was connected to the optical power meter. The radiation power in both fibers was approximately the same. The polarization control was carried out via special polarization rotator.

3. Experimental results and discussion

Temperature dependence of the detector resistance together with the current-voltage characteristic at the operating temperature is shown in the figure 3. There are two superconducting transitions. First one at \( T_{c1} = 8.3 \) K corresponds to the transition of the detector sensitive element. The second one at \( T_{c1} = 6.5 \) K occurs due to the proximity effect in the NbN film under the Au contacts.

Figure 4 shows the dependence of the detector response on the absorbed power of the laser. The absorbed power was estimated using the well-known technique described in [8]. The planar sizes of the detector sensitive element were 0.15×1.5 µm². The upper limit of the 3-dB detector dynamic range corresponds to the absorbed power of 220 nW. The minimum detected signal determined by the intrinsic device noise corresponds to the absorbed power of 8.5 nW, thus the detector dynamic range is about 14 dB.

The inset in figure 4 shows the time transient of the device response. The risetime of the pulse is about 130 ps determined by properties of the RF line. The falltime is about 0.4 ns. The pulse duration is \( \tau_0 = 250 \) ps at half maximum. The obtained detector intrinsic noise equivalent power is \( NEP_{Rx} = 1.1 \times 10^{-13} \) W·Hz⁻⁰·⁵. This result is in good agreement with that obtained in [6]. The detector energy resolution is about \( \delta E = NEP_{Rx} \tau_0^{0.5} = 2 \) aJ.
Figure 3. The detector resistance-temperature curve. Inset shows the current-voltage characteristic of the detector at the operating temperature.

Figure 4. The output of the detector versus the absorbed power. Detector 3-dB dynamic range is marked with the blue lines. Inset shows the time transient of the device response from a 1.55-μm laser pump with pulse duration of less than 50 ps.

4. Conclusion
Finally, performance of the fast and sensitive bolometric detector based on hot-electron effect in ultra-thin superconducting films has been demonstrated. The directly measured energy resolution of this detector is about 2 aJ and the internal response time is less than 130 ps. This detector is a device-of-choice for a number of important practical applications associated with pulsed THz radiation.
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