Background-limited operation of 4K-cryocooled THz photoconductive detector system with a wide frequency range of 0.8 to 4THz

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***Abstract*—We have demonstrated a terahertz (THz) detector system which employs three terahertz photoconductive semiconductor detectors to realize a response to a wide frequency range of 0.8 to 4THz and a mechanical 4K GM refrigerator instead of a liquid helium container to perform practical and convenient use. Optical and electrical performance of the THz detector system was evaluated at an operation temperature of 4K under 300K background radiation environment, which have proved the detector system can achieve background limited NEP (noise equivalent power) for THz detection even if vibration noise of mechanical cooler is present.**

I. Introduction

AFTER the recent innovative development in terahertz (THz) technology including the THz time-domain spectroscopy (TDS) [1], [2] (also see ref. [3]) and the THz quantum cascade laser (QCL) [4], many studies have been carried out to make progress in THz technology and to develop various applications for security, defect-inspection and analysis in industry, bio-medicine, pharmacy etc (e.g. see ref. [5]) by utilizing unique characteristics of the THz wave, which are transparent to such materials opaque at visible light, much safer for health as compared to X-ray, and higher spatial resolution than radio waves and also existence of fingerprint spectra of bio-macromolecules. There still remains however so-called "Terahertz Gap" also in detector technology.

It is necessary for obtaining high detectivity in the THz region to cool detectors with liquid helium so far, by which very high performance has been obtained for both a bolometer [6] and a photoconductor [7]. Use of such coolant as liquid helium is very troublesome and needs high cost.

We therefore study a high performance THz detector system which can be operated without utilizing the liquid helium, that is we adopt a 4K mechanical refrigerator and THz photoconductive detectors which have much higher responsivity than composite bolometers and are robust against vibration by the mechanical cryocooler.

Spectral response of the photoconductive detector has a proper cutoff frequency at the lower side which corresponds to ionization energy for generating free carriers, and it decreases from the cutoff frequency to higher frequencies approximately in proportion to inverse of frequency. We therefore adopted three photoconductive detectors with different cutoff frequencies to cover wide range of THz frequencies.

This paper describes the design and performance of the 4K-cryocooled THz photoconductive detector system with a wide frequency range of 0.8 to 4THz for sensing objects under the 300K background radiation.

II. Instruments

The THz detector system comprises of a compact 4K-cryocooler cryostat with a low-vibration cold work surface, four detector mounts with cold THz filters and light-collecting optics, and low-noise preamplifiers.

The 4K-cryocooler is a two-stage GM mechanical cooler and its cold head is structurally isolated from but thermally connected to the cold work surface on which detectors are installed. Measured vibration amplitude of the cold work surface was less than 2.6 μ m which was much smaller than the ordinary level of 10 μ m of the GM cryocooler cryostat. Temperature of the cold work surface decreases to below 4 K within 5.5 hours after switching on.

Figure 1 shows the configuration of detector mounts on the cold work surface. Two detector mounts look one direction through cold filters and a z-cut crystal window, whereas the other two look the opposite direction.

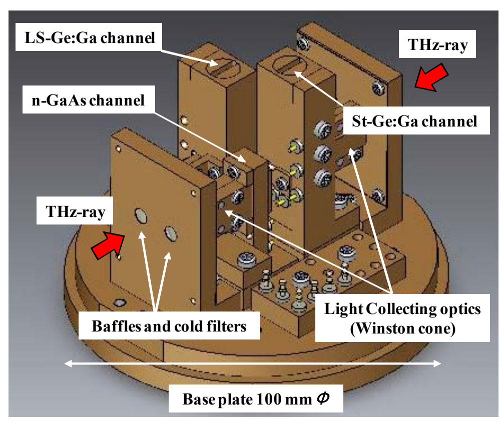

Figure 1: Configuration of detector mounts on the 4K cold work surface.

Three of four detector mounts are planned to be occupied by sensitive THz extrinsic photoconductive detectors with different impurity ionization energies, which have been developed for space astronomical observations so far, and another one is supposed for testing new THz detectors. The high frequency channel uses a p-Ge:Ga photoconductive detector having an acceptor level of 10.8meV corresponding to

978-1-4244-5417-4/09/$26.00 ©2009 IEEE

response in the frequency range of 2.8-4.0THz[7], [8]. The Ge: Ga can be replaced by a Ge:Ga detector strained by only small stress of about 600kg/cm^2, which is named a lightly stressed Ge:Ga (LS-Ge:Ga) having much higher responsivity as discussed in the next section. The middle frequency channel adopts a stressed Ge:Ga (St-Ga:Ga) detector, strained by a maximum stress of ~6000kg/cm^2, having an acceptor level of about 5.4meV and detection frequencies in the range of 1.5-3.0THz[9], [10]. The low frequency channel is an n-GaAs detector with a donor level of 5.7meV and having response to photons with energy above 4.3meV through photo-thermal effect, corresponding response to 0.8-1.6THz frequency radiation[11], [12].

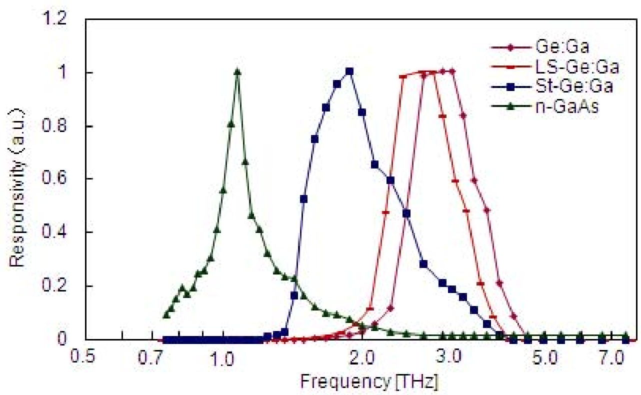

Figure 2: Spectral responses of Ge:Ga, lightly stressed Ge:Ga, stressed Ge:Ga, and n-GaAs photoconductive detectors.

Figure 2 displays the spectral responses[13], [14] of four photoconductors, in which respective peak responsivity is normalized as one. The spectral response of lightly stressed Ge:Ga is drawn by shifting that of Ge:Ga to lower frequency.

Trans-impedance-type preamplifier circuits for the THz photoconductive detectors were designed for realizing low noise and high-speed response, in which feedback resistors of 1 MEG are cooled with detectors.

III. Performance Evaluation

Dark currents of Ge:Ga, LS-Ge:Ga, stressed Ge:Ga and n-GaAs photoconductors were measured at bias voltages of about a respective half breakdown voltage under sufficiently low background radiation as a functions of temperature, which results are shown in Figure 3. The lowest currents of Ge:Ga and LS-Ge:Ga are limited by noise in the measurement, whereas the dark current of n-GaAs shows hopping current at below 5 K.

As lower the temperature, the dark current decreases rapidly because thermal excitation of carriers from impurities reduces. The dark current is expressed by Eq. (1).

$$i_d \propto T^{3/2} \exp(-E_i/kT), \qquad (1)$$

where i_d is dark current, T is temperature, E_i is impurity ionization energy, and k is the Boltzmann constant. The impurity ionization energies are estimated by fitting Eq. (1) to the dark currents in Fig. 3. The results are E_i =10.4, 9.40, 5.25, and 4.34 meV for the Ge:Ga, LS-Ge:Ga, St-Ge:Ga , and n-GaAs photoconductive detectors respectively.

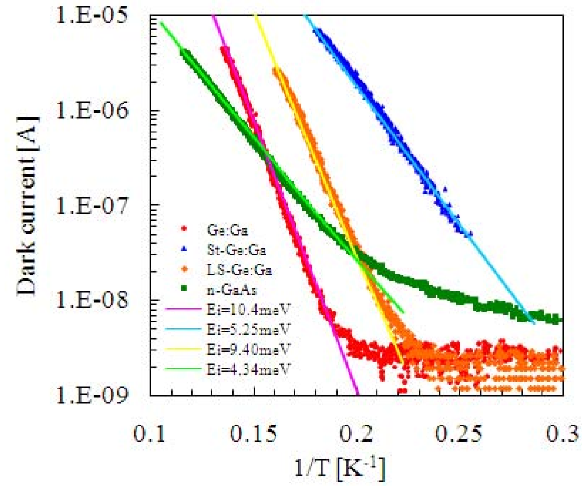

Figure 3: Dark currents of four photoconductive detectors as functions of temperature.

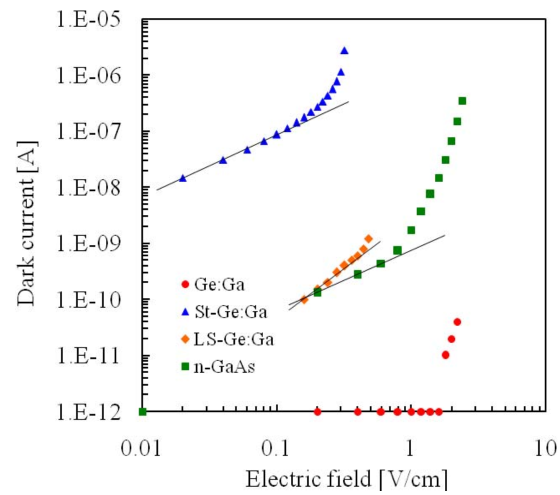

Figure 4: Dark current vs. electric field characteristic of four THz photoconductive detectors operated at 4K.

The dependences of dark current on bias electric field are measured for Ge:Ga, LS-Ge:Ga, St-Ge:Ga and n-GaAs at 4K as shown in Fig. 4. The normal I-V characteristics are observed, which are the ohmic region at lower electric field, and the hot carrier region at higher field, and the breakdown at the highest field. The breakdown electric fields of Ge:Ga, LS-Ge:Ga, St-Ge:Ga, and n-GaAs photoconductive detector were 2.2, 0.48, 0.32, and 2.4 V/cm, respectively.

Responses to the THz radiation of the photoconductive detectors at appropriate bias voltages were measured using a black-body radiator of temperatures around 1000K for both DC mode and 20-Hz optical-chopping mode. Responsivity is evaluated by compare the measured photocurrent with the input THz energy flux (or photon flux) estimated by the blackbody radiation, transmittance of THz filters, efficiency of optical elements and atmospheric transmittance. The responsivities of four photoconductive detectors are listed in Table 1 together with respective breakdown field, bias electric field, cutoff frequency, background photon influx and background-limited noise voltage in Table 1. Responsivity for 20Hz-optical

chopping is a little smaller than that of DC measurement because the optical efficiency of chopping is less than one.

Table 1: Optical and electrical performances of four photoconductive detectors operating at a temperature of 4.0K

detector	Ge:Ga	LS-Ge:Ga	St-Ge:Ga	n-GaAs
Breakdown field [V/cm]	2.2	0.48	0.32	2.8
Bias field [V/cm]	1.0	0.20	0.10	2.4
Ionization energy [meV]	10.4	9.4	5.3	4.3
Cutoff frequency [THz]	2.5	2.3	1.3	1.1
Background photon influx [photons/s]	5.1E+13	3.6E+13	5.8E+13	8.0E+12
Noise voltage density (Background-limit)	3.3E-07	2.9E-06	3.3E-06	2.9E-07
Responsivity (DC) [A/W]	1.0	12	33	0.29
ηG^* (DC)	0.010	0.11	0.18	0.0013
Responsivity (AC**) [A/W]	0.77	7.1	19	0.21
ηG^* (AC**)	0.0080	0.066	0.097	0.00091

* η G is the product of quantum efficiency and photoconductive gain.
**Optical chopping at 20 Hz.

The responsivity of LS-Ge:Ga is more than ten times of that of Ge:Ga though the cutoff frequencies are not so different, which is mainly originated from longer lifetime of free holes in the stressed p-type impurity semiconductors[15].

The responsivity of n-GaAs detector was not very high, but it increased at temperatures higher than 4K because the photo-thermal effect helped the ionization of carriers to the conduction band more efficiently. This effect was however small at a large bias voltages near the breakdown.

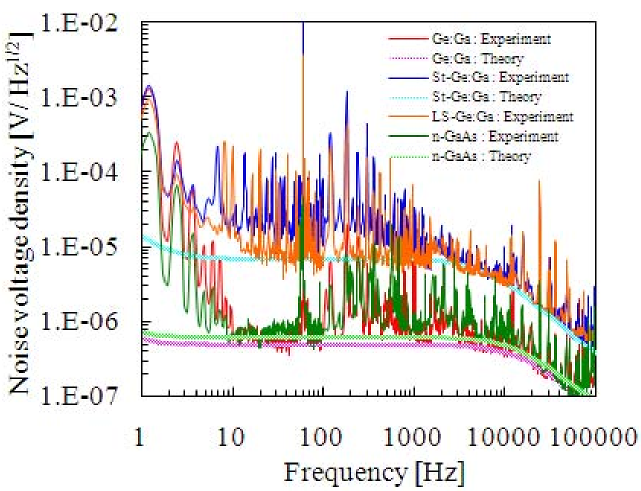

Figure 5: Noise voltage density of THz photoconductive detectors in the 4K cryocooler cryostat under 300 K background radiation.

The noise voltage densities of the THz photoconductive detectors in the 4K-cryocooler cryostat were measured under the 300 K background THz radiation of around 10^{13} photons/s. The noise spectra of four photoconductive detectors are almost flat at between 10 Hz and 10 kHz except for peaks of vibration noise due to mechanical cooling as shown in Fig. 5.

The measured noise comprises a square-root of the squared sum of the detector noise consisting of photon, thermal and generation-recombination noises, the thermal noises of feedback and grounding resisters, and the input-noise current and voltage of operational amplifier, in which the photon noise is the main component in our detector system. The total noise at the preamplifier output calculated for the four detectors are also shown by solid curves in Fig. 5. The measured noises are almost consistent with the theoretical values, which mean the 4K-cryocooled THz photoconductive detector system works by background radiation limited performance.

IV. CONCLUSION

We have developed a THz photoconductive detector system, having a wide frequency range from 0.8 to 4THz, cooled by a practical mechanical 4K refrigerator. Optical and electrical performance of the THz detector system shows that it functions a background limited performance under the 300K background radiation even if vibration noise of mechanical cooler is present.

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