3-2 Study for Far-infrared and Faint Light Detection Technology

FUJIWARA Mikio, AKIBA Makoto, and SASAKI Masahide

To realize a sensitive photodetector, cooling down the device is a effective way because of reducing thermal noise and dark current. Recent space observation satellites have liquid-Helium cooled detectors. We focus on far-infrared region, in which there are many important research fields. To our knowledge, we are the first to successfully report a direct hybrid two-dimensional detector array in the far-infrared region. Moreover, we are trying to develop an ultra-sensitive photodetector for the application in quantum information field by using cryogenic technology.

Keywords

Far-infrared detector, Cryogenic temperature, Two-dimensional array, Detection of faint light

1 Introduction

Electromagnetic waves are visible to the human eye at wavelengths of 0.3 to 0.75 μm. The term “infrared” refers to light at wavelengths longer than those of visible light. Specifically, infrared rays are electromagnetic waves with wavelengths ranging from 0.75 μm to 1 mm. In this paper, far-infrared rays are defined as electromagnetic waves with wavelengths of 30 μm to 1 mm.

At temperatures above absolute zero, all matter emits temperature-dependant electromagnetic waves due to the motion of surface atoms or molecules. In the far-infrared region, rotational spectra of molecules can be observed. And there are many important scientific research fields in this region, such as the vibration mode of impurities in solids or plasma diagnosis[1]-[3]. In astronomical observation, measurement of far-infrared thermal radiation from interstellar dust has revealed an extraordinary amount of information about the birth of stars, and important indicators of galactic activity. However, there is no established method of observation of light in this wavelength region, due to the technical difficulties involved.

In light of the present situation, we initiated a project to develop a far-infrared detector for the 50 to 110-μm waveband, to be mounted on Japan’s first infrared space observation satellite, the ASTRO-F, slated for launch by the Japan Aerospace Exploration Agency (JAXA) in the summer of 2005. A gallium-doped germanium extrinsic semiconductor has an acceptor level of 10.8 meV[4], and has been used as a sensitive far-infrared detector with a cutoff wavelength of 110 μm. To minimize thermal excitation to the acceptor level and to maximize sensitivity, the detector is cooled to the temperature of liquid helium (4.2 K) or lower.

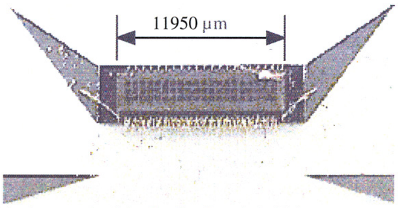
Ge:Ga far-infrared detectors have long been known as the most sensitive quantum photodetectors in this wavelength region, however, necessity of cooling and the fact that far-infrared radiation is mostly absorbed by the atmosphere hinder commercial development of photodetector in this region. In our development efforts, we focused on creating a compact far-infrared detector array that would enable efficient and accurate space observation and at the same time be suitable for installation on a satellite. To our knowledge, we are the first to successfully report a direct hybrid structure of a monolithic two-dimensional array and readout circuit with high responsivity and fill factor in the far-infrared region.

In this paper, we describe the performance of our Ge:Ga direct-hybrid two-dimensional array and present the results of research into the establishment of a 1.5-μm-band photon-number resolving detector based on cryogenic readout technology for use in today's advanced quantum information applications.

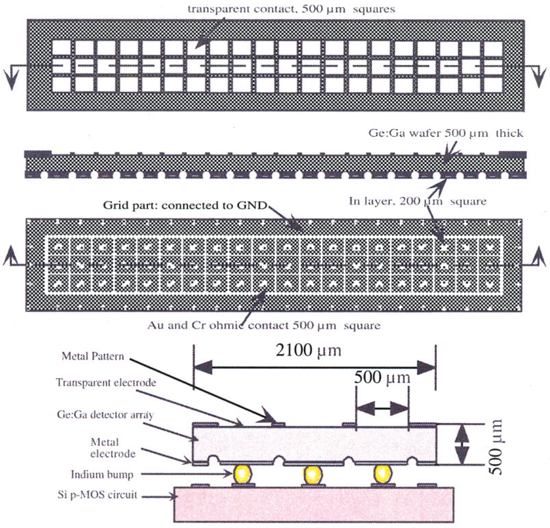
2 Ge:Ga far-infrared detector direct-hybrid two-dimensional array

A large format array detector can expand the available observation region while maintaining the same spatial resolution, for improved efficiency and accuracy in measurement and observation. Conventional Ge:Ga far-infrared detectors of this type were set inside cavities in order to improve quantum efficiency. Such an array structure, however, makes it difficult to achieve a high-density array and also increases the overall weight of the system. On the other hand, a monolithic array, in which multiple elements are arranged on a single wafer, offers a suitable structure for high-density packaging. Unfortunately, to date the low optical absorption coefficient of Ge:Ga photodetectors has been an obstacle to the successful development of high-responsivity detectors.

The optical absorption coefficient of Ge:Ga can be increased by increasing the Ga dopant density, but high dopant density results in an increase in the hopping currents that flow between impurity levels and degradation of detection limit. Although an increase in the volume of the detector extends the optical absorption length, this method is not suitable for use in space, where the device is exposed to enormous amounts of high-energy particles. High-energy particles hitting a Ge:Ga detector increase responsivity nonlinearly, resulting in significant degradation of measurement accuracy. To minimize the impact of high-energy particles, miniaturization is essential for any detector element that is to be mounted on a satellite. Furthermore, since this sort of detector features high impedance, a trans-impedance amplifier is necessary for signal extraction. To reduce microphonic noise, trans-impedance must be conducted near the detector. To satisfy these requirements, we made use of a monolithic two-dimensional array with an ion implanted layer sensitive to far-infrared radiation, a readout circuit operating at the same temperature as the Ge:Ga detector, and In-bump technology for direct connection of the array and the circuit. Figure 1 shows the structure of our direct-hybrid two-dimensional array.



(a) photograph of the Ge:Ga direct hybrid detector array



(b) conceptional cross section of the Ge:Ga direct hybrid detector array

Fig. 1 (a) Photograph and (b) conceptual cross-sectional view of Ge:Ga direct hybrid array.

Our detector is comprised of 20 elements arranged in 3 rows. A lattice pattern was formed by the deposition of Cr and Au on the front surface of the monolithic array, which has a role as an electrode and optical separator for each pixel. The bottom electrode was formed by the deposition of Cr and Au over the entire surface. When far-infrared radiation enters through the surface layer, it generates a photocurrent, which is then read by the bottom electrode. The front surface is a transparent electrode, and is common to all elements.

The elements are separated by grooves on the bottom electrode measuring 100 μm in width and 30 μm in depth. The light-receiving area of each element measures 500 μm by 500 μm, and the elements are arranged with a center-to-center distance of 550 μm and an electrode-to-electrode distance of 500 μm. A capacitive trans-impedance amplifier (CTIA) constructed with a p-type Si MOSFET is adopted for the readout circuit, which was developed by a team led by Nagoya University. Because the detector is cooled to a temperature of 2.5 K, strain of approximately 12 μm is generated, due to the different coefficients of thermal expansion between the Ge:Ga far-infrared detector and the readout circuit with the base material of Si, when cooling the materials from room temperature. To absorb this strain, a direct-hybrid structure was constructed using indium (In) technology, which features a low Young's modulus even at cryogenic temperatures.

Due to the significant strain, the conventional deposition method was not used to form the In bumps. Instead, indium balls, each with a diameter of 100 μm, were arranged at the detector intervals. Thermo-sonic was applied when forming the direct-hybrid structure. Figure 2 shows an SEM photograph of the In bumps and a soft-X-ray photograph of the direct-hybrid array. These photos indicate the successful formation of smooth bumps.

The entrance surface and the bottom electrode of the Ge:Ga semiconductor were dosed with high-density B having the same acceptor level as Ga, thus allowing for easy carrier tunneling to the electrode. The B injection layer also plays an important role in improving the responsivity of the detector. By forming the B injection layer with a density level below the Mott transition, we succeeded in establishing sensitivity to far-infrared radiation. Although a number of attempts have been made in the past to realize a BIB structure using the ion implanting method, there was a notable tendency to neglect the activation rate in the injection of B. In our research, we proved that the activation rate of B in the Ge crystals was an important parameter determining the characteristics of the ion injection layer[5].

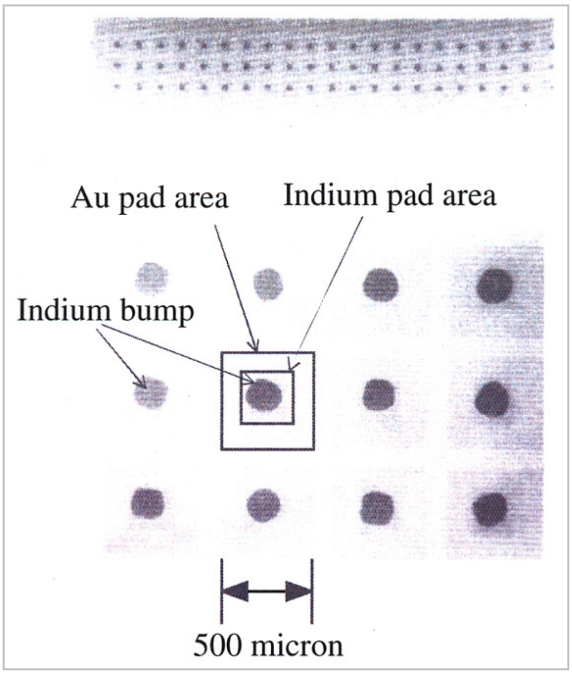


Fig.2 *Soft-x-ray photograph of the direct hybrid array.*

To verify the effect of the B injection layer on the improvement of Ge:Ga far-infrared detector performance, we evaluated a longitudinal-type Ge:Ga detector using a trans-impedance amplifier (TIA) circuit with feedback resistance of 6 GΩ, which incorporated a performance-proven 77-K operating Si JFET. Figure 3 indicates the dependence of sensitivity and noise-equivalent power (NEP) on bias field strength.

Since the B density is high, the optical absorption coefficient takes a large value. Moreover, due to the presence of low-density Ge:Ga between the electrodes, generation of

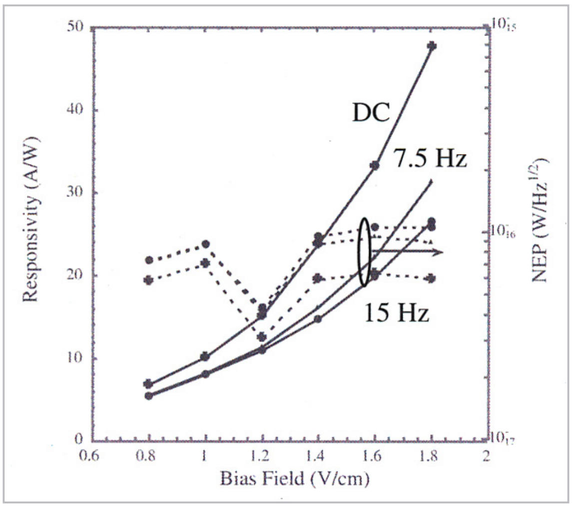


Fig.3 *Responsivities and NEPS as functions of the bias field. Squares, step change in the photon influx (dc); triangles, 7.5-Hz chopped light; circles, 15-Hz chopped light. Solid curves, responsivities; dashed curves, NEPS.*

dark currents due to hopping currents is suppressed. Through this B injection layer, we were able to increase quantum efficiency to 42%, as compared to an efficiency of 19% for the Ge:Ga bulk region only. As a result, a high sensitivity of 15 A/W was achieved, along with a small size (500×500×500 μm), and without the need for a cavity. Compared to the detector[6] installed on the SIRTF infrared observation satellite launched by the United States in August 2003, our detector array has more than twice the responsivity at 1/6 the size.

Our cryogenic readout circuit is a CTIA that uses a p-type Si MOSFET and offers an open loop gain of 1,000 times with a feedback capacity of 7 pF. The noise of the detector and readout circuit exhibited a 1/f-dependent spectrum of 20 μV/Hz$^{1/2}$ at 1 Hz. It is known that this noise is generated by the readout circuit. The time signal is integrated in 0.14 seconds in the survey mode of the ASTRO-F. Estimation of the NEP using correlation double sampling (CDS) yielded a value of 1.8×10^{-17} W, indicating that performance is sufficient for use in observation equipment. With these results we have developed the world's first far-infrared detector direct-hybrid array[7]. Figure 4 shows the output waveform from the direct hybrid array.

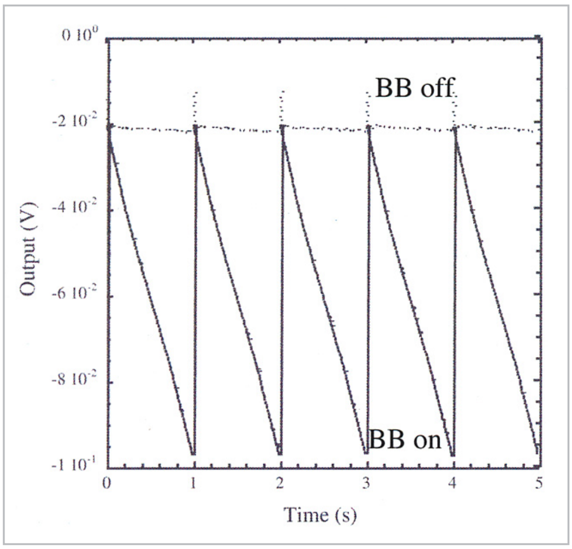


Fig.4 *Output waveform of the Ge:Ga direct hybrid array at 2.15K. Integration time was 1 sec, and the bias field was 1.8V/cm. Solid curve is for the BB source on; dashed curve, for the BB source off.*

3 Faint-light detection technology

Cryogenic circuit technology can be applied not only to far-infrared detection but also to the detection of faint light at any wavelength. Devices such as a high-sensitivity photodetector with high impedance and a low-noise readout circuit that performs trans-impedance and amplification can be powerful device for applications of detecting faint light sources such as spectroscopy. These devices are expected to play key roles in the quantum information field in the future, particularly in the realization of high-volume, and unconditionally secure. A photon number resolving detector (which accurately counts the photons in an optical pulse) can improve quantum cryptography, and will be an essential device in quantum computation in the optical region. For example, by combining non-classical light such a single-photon state or squeezed state with a photon-number resolving detector and a feedback system, it will be possible to construct a general-purpose quantum computing machine. This technology will prove critical not only in quantum coding technology for future large-capacity communications, but will also serve as a basis for the construction of high-security quantum information networks. Therefore, the impact of this technology has potential influence.

Stanford University in the United States has developed a visible-light photon counter (VLPC) operating at 10 K [8]. Further, a photon number resolving detector was developed in NIST and was made from a superconductor, with an operation temperature of 100 mK [9]. It can count photon numbers in the 1.5-μm infrared light band, in which the attenuation rate of an optical fiber is minimum. These detectors have a number of shortcomings: high dark count, susceptibility to background light, and low quantum efficiency, to cite a few. Furthermore, these detectors require special fabrication techniques, a major obstacle to widespread use.

Our research is aimed at the development of a photon-number resolving detector for 1.5-μm-band infrared light through a combination of commercially available devices operating at cryogenic temperatures. The method we have adopted counts photons in the incident light through accurate determination of the electric charge generated in the InGaAs pin photodiode. The readout circuit system uses a charge integration amplifier (CIA), which is suitable for faint-light detection and requires a minimum number of components. The circuit diagram is shown in Fig.5. The section surrounded by the red line is cooled to a temperature of 4.2 K. For the InGaAs pin photodiode, we used a ϕ30-μm type, from Kyosemi.

Low-capacity circuit packaging and reduction of noise in the readout circuit determines the feasibility of photon number resolving detection. In our research we adopted a GaAs JFET for the primary amp. A number of FETs are available that operate at cryogenic temperatures, such as MOS FETs, MES FETs, HEMTs, and compound JFETs. In n-type MOS FETs, the kink phenomenon—a sudden increase in current—is observed among the various current and voltage characteristics seen at cryogenic temperatures. To avoid this kink phenomenon, it is necessary to use a p-type MOS FET [10] or to increase the amount of dopant [6]. Even with such measures, noise remains at approximately 10 $\mu V/Hz^{1/2}$ at 1 Hz, insufficiently low.

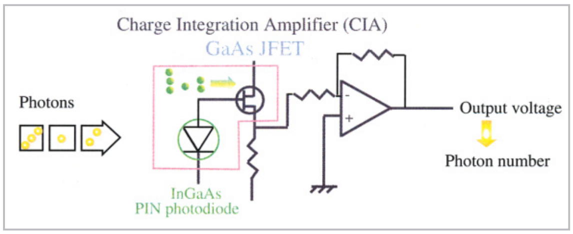


Fig.5 *Faint light detection system at 1.5μm with charge integration amplifier. Parts in the frame are cooled to 4.2K.*

It has been reported that noise may be reduced to low levels (below 1 $\mu V/Hz^{1/2}$ at 1 Hz) in MES FETs and HEMTs with a drain current of approximately 1 mA [11], but these FETs consume a large amount of power, which is a fatal defect for cryogenic electronics, and also feature significant gate leak current; these devices are therefore unsuitable for use in the readout circuits of high-impedance detectors. On the other hand, a compound (GaAs) JFET uses a p-n junction in its gate structure and can provide higher gate impedance than HEMTs and other devices. Furthermore, the carrier-traveling channel and gate electrode distances in a compound (GaAs) JFET are longer than in other FETs, resulting in a lower input capacity given the same gate size. This means that a compound JFET has the major advantage of providing a higher S/N ratio in an integration-type readout circuit.

We evaluated the performance of the SONY GaAs JFET at cryogenic temperatures. Figure 6 (a) shows the I-V characteristic of a GaAs JFET with a gate width of 5 μm and a gate length of 50 μn at 4.2 K, and Figure 6 (b) indicates the dependence of mutual conductance on gate voltage. As shown in the graph, the I-V characteristic was favorable at 4.2 K, thus confirming the possibility of achieving trans-conductance of approximately 10 μS.

Figure 7 shows the dependence of gate capacity on the gate voltage at room tempera-

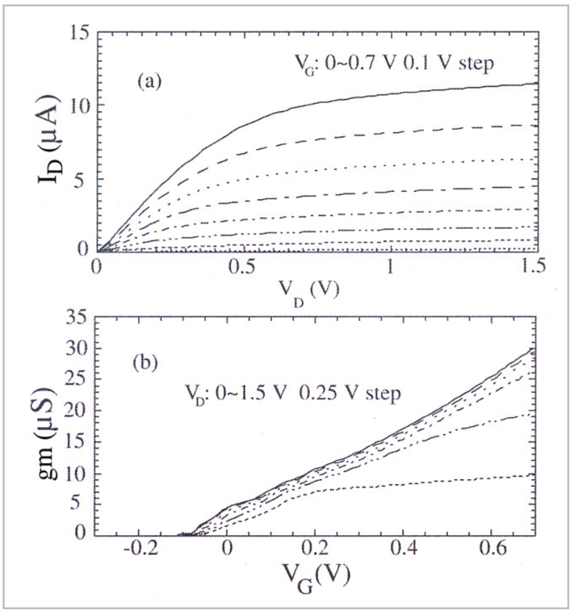


Fig.6 Drain current vs drain voltage curves with gate bias as a parameter. (b) Transimpedance as a function of gate voltage with drain voltage as a parameter.

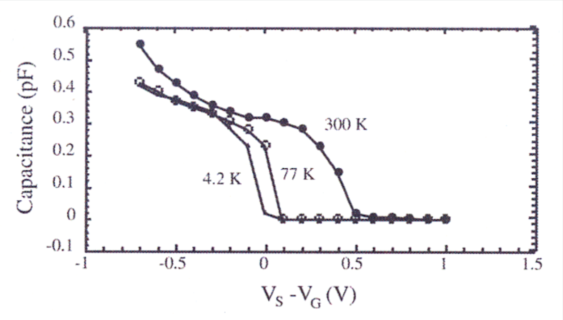


Fig.7 Gate capacitance as a function of gate-source voltage with operation temperature as a parameter.

ture, 77 K, and 4.2 K. The lower the temperature, the lower the capacity. At 4.2 K, operation below 0.1 pF becomes possible. At this cryogenic temperature, a type of noise [12] referred to as “random telegraph signal” (RTS) is generated in the GaAs JFET (Fig.8). This switching phenomenon results in significantly disruptive measurement deviation.

We have developed a method of substantially reducing the probability of RTS generation, in which the elements are heated above 35 K with a drain current, followed by recooling to 4.2 K. We have designated this process as “thermal cure” (TC). Figure 9 shows noise levels with and without TC.

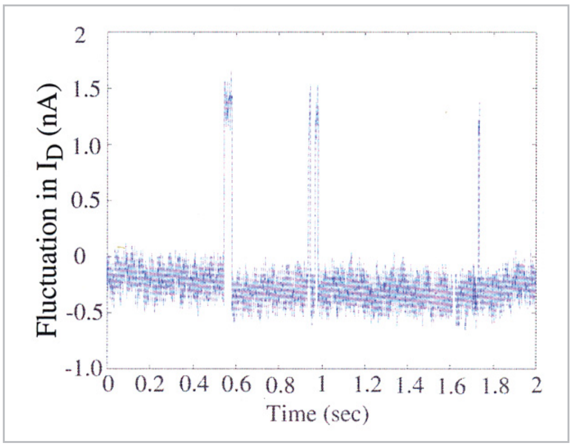


Fig.8 Typical fluctuation in drain current I_D with an RTS amplitude of ~0.1%, V_D=0.75V, V_G=0.32V, at 4.2K.

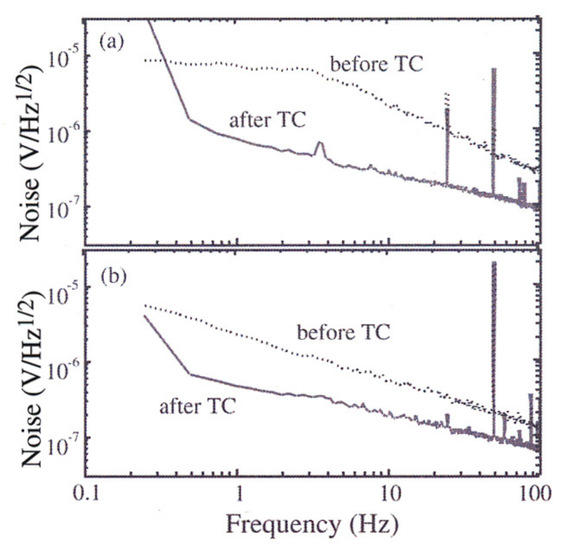


Fig.9 Noise spectra of the GaAs JFET both before and after TC. (a) V_D=0.75V, V_G=0.32V, (b) V_D=0.5V, V_G=0.21V.

Without TC, noise was approximately 3 μV/Hz$^{1/2}$ at 1 Hz, while the application of TC reduced this noise to 0.5 μV/Hz$^{1/2}$ at 1 Hz. For details of the mechanism involved, please refer to Document [13].

Further, measurement of gate input capacity of the GaAs JFET returned a value of 0.06 pF, while the InGaAs pin photodiode displayed a capacity of 0.026 pF at a cryogenic temperature. When this was combined with the input capacity of the GaAs JFET, total capacity was 0.086 pF (Cs), lower than 0.1 pF. We also attempted to detect faint light using a CIA-type readout circuit. If the signal is expressed by QGM/Cs (V), noise is $V_{n,CDS}$, Q is the elementary electric charge (1.6×10^{-19} C), and GM is the source follower gain (0.8 to 0.9), then noise ($V_{n,CDS}$) at CDS can be expressed by the following equation.

$$V_{n,CDS}^2 = \int_0^\infty V_n(f)^2 \frac{4\sin^2(\pi f T)}{1+\left(f/f_c\right)^2} df \qquad (1)$$

Here, T is the integration time (0.5 or 1 s), and f_c (100 Hz) is the circuit's cut-off frequency. $V_n(f)$ refers to the noise spectrum. Figure 10 shows the output waveform when the incident light was attenuated to approximately 40 photons per second. Quantum efficiency was approximately 60%. Although there was an acquisition failure due to RTS, we were able to achieve detection with a deviation of 2 photons, corresponding to the estimated accuracy based on the applicable noise level. The leak current of this circuit was 500 electrons/hour and thus had no practical effect on measurement. In short, this can be regarded as the most sensitive detector in the world, with minimal dark count in the 1.5-μm band. Our next goals consist of reducing noise further in the readout circuit and developing a detector featuring single-photon accuracy.

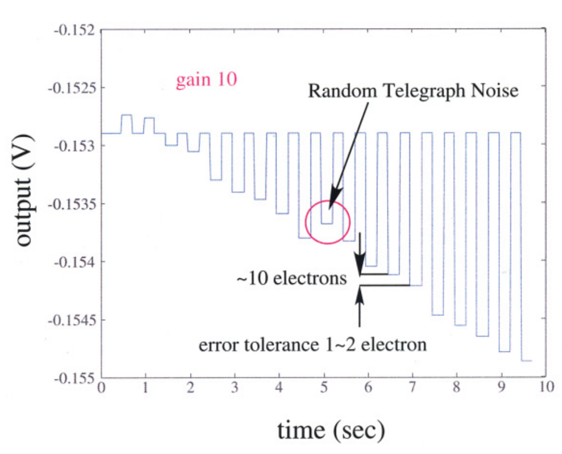


Fig.10 Photo-counting waveform of the InGaAs pin photodiode with CIA at 4.2K.

4 Summary

Working to develop highly sensitive low-noise photodetectors through experimentation at cryogenic temperatures, we have designed the world's first direct-hybrid structure for a Ge:Ga far-infrared detector, and have succeeded in the detection of far-infrared light. Furthermore, we have constructed a 1.5-μm-band faint-light detector using an InGaAs pin photodiode and a GaAs JFET, successfully detecting light at about 40 photons per second with a quantum efficiency of 60% and a deviation of 2 photons. We plan to reduce noise further in the future, as part of our efforts to further improve photon-number resolution.

References

1 C. A. Beichman, "The IRAS View of the Galaxy and the Solar System", Ann. Rev. Astron. Astrophysics, 35, 521-563, 1987.

2 D. M. Mittleman, R. H. Jacobsen, and M. C. Nuss, "T-ray Imaging", IEEE J. Sel Topics Quantum Electron, 2, 679-692, 1996.

3 M. Hermann, M. Tani, K. Sakai, and R. Fukasawa, "Terahertz imaging of silicon wafers", J. Appl. Phys. 91 (3), 1247-1250, 2002.

4 P. R. Bratt, "Impurity germanium and silicon infrared detector" in Semiconductors and Semimetals, R. K. Willardson and A. C. Beer, eds. (Academic Press, New York, 1997), pp. 33-142.

5 M. Fujiwara, "Development of far-infrared Ge:Ga photoconductor having a longitudinal configuration," Appl. Phys. Lett. 77, 3099-3101, 2000.

6 E. T. Young, J.T. Davis, C.L. Thompson, G.H. Rieke, G. Rivlis, R.Shchnurr, J. Cadien, L. Davidson, G. S. Winters, and K. A. Kormos, "Far-infrared imaging array for SIRTF," in Infrared Astronomical Instrumentation, A.M. Fowler eds,. Proc. SPIE 3354, 57-65, 1998.

7 M. Fujiwara, T. Hirao, M. Kawada, H. Shibai, S. Matsuura, H. Kanneda, M. Patrashin, and T. Nakagawa, “Development of a gallium-doped germanium far-infrared photoconductor direct hybrid two-dimensional array,” Appl. Opt. Vol. 42, No. 12, 2166-2173, 2003.

8 E. Waks, K. Inoue, W. D. Oliver, E. Diamanti, and Y. Yamamoto, “High efficiency photon number detection for quantum information processing,” quant-ph/0308054v1, 2003.

9 A. J. Miller, S. W. Nam, J. M. Martinis, and A. V. Sergienko, “Demonstration of a low-noise near-infrared photon counter with multiphoton discrimination,” Appl. Phys. Lett. Vol. 83, No. 4, 791-793, 2003.

10 T. Hirao, Y. Hibi, M. Kawada, H. Nagata, H. Shibai, T. Watabe, M. Noda, and T. Nakagawa, “Cryogenic readout electronics with silicon P-MOSFETs for the infrared astronomical satellite, ASTRO-F,” Advances in Space Research, 2002.

11 R. K. Kirschman and J. A. Lipa, “Further evaluation of GaAs FETs for cryogenic readout,” in Infrared Detectors and Instrumentation, W.H. Makky eds,. Proc. SPIE 1946, 350-364, 1993.

12 K. Kandiah, “Random telegraph signal currents and low-frequency noise in junction field effect transistors,” IEEE trans. Elec. Dev. Vol. ED-41, No. 11, 2006-2015, 1994.

13 M. Fujiwara, M. Sasaki, and M. Akiba, “Reduction method for low-frequency noise of GaAs junction field effect transistor at a cryogenic temperature,” Appl. Phys. Lett. Vol. 80, No. 10, 1844-1846, 2002.

***FUJIWARA Mikio**, Ph. D.*

Senior Researcher, Quantum Information Technology Group, Basic and Advanced Research Department

Photodetection Technology

***AKIBA Makoto**, Ph. D.*

Senior Researcher, Optoelectronics Group, Basic and Advanced Research Department

Optical Sensing

***SASAKI Masahide**, Ph. D.*

Leader, Quantum Information Technology Group, Basic and Advanced Research Department

Quantum Information Theory