Modulation-Doped AlGaAs/InGaAs Thermopiles for Uncooled IR-FPA Utilizing Integrated HEMT-MEMS Technology

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BIOGRAPHY

Masayuki Abe received the B.E., M.E., and Ph.D. degrees in Electrical Engineering from Osaka University, Osaka, Japan, in 1967, 1969, and 1973, respectively. In 1973, he joined Fujitsu Laboratories, Ltd., Japan, where he was engaged in developing AlGaAs and InGaAsP LEDs for fiber communications, microwave HEMTs for DBS receivers, high-speed HEMT LSIs for supercomputers. Since 1998, he has been engaged in developing ten kilowatt class high power h-GaN HEMTs for solar-cell & fuel-cell inverters of co-generation systems, high power 3C-SiC vertical DMOSFETs and c-GaN HEMTs for EV/HEV inverters, modulation doped heterostructure thermopiles (H-PILE) for uncooled infrared image-sensor at KRI Inc. and 3D-bio Co., Ltd. He has authored more than 200 scientific publications and 11books. He is a Life Fellow of IEEE. He is currently President at HEMTCORE and 3D-bio Co., Ltd. He received the Distinguished Contributed Paper Award of the Laser Society of Japan in 1980, the International Prize of SIOA in Italy in 1987, and the Best Poster Award of ICMAT, MRS in 2005. He served as Overseas Advisor for the IEEE GaAs IC Symposium (1983-1985), a Guest Editor of the IEEE Transactions on Electron Devices for the May 1986 Special Issue on Heterojunction Field-Effect Transistors (HFET), and a Lecturer for a short course at the 1990 IEEE GaAs IC Symposium. He served as Technical Committee Member of MITI(METI) of Japan for many National R&D Projects on GaAs and HEMT related technology (1981-1996).

TECHNICAL ABSTRACT

Novel thermopiles based on modulation doped AlGaAs/InGaAs heterostructures are proposed and developed for the first time, for uncooled infrared FPA (Focal Plane Array) image sensor application. The high responsivity R with the high speed response time τ are designed to be 4,900 V/W with 110 µs. Based on integrated HEMT-MEMS technology, the 32x32 matrix FPAs are fabricated to demonstrate its enhanced performance by black body measurement. The technology presented here demonstrates the low cost potentiality for uncooled infrared FPA application.

DEVICE DESIGN AND FABRICATION: The AlGaAs/InGaAs sensors have been fabricated utilizing the integrated HEMT-LSI technology[1]. The schematic cross sectional structure of thermopile for modulation-doped AlGaAs/InGaAs on a GaAs substrate is shown in Fig. 1 [2],[3]. To realize the p-/n-*H*eterostructure thermo*PILE* (H-PILE), a stack of epitaxial layers on a semi-insulating GaAs substrate was grown by MOCVD. The stacked epitaxial structure with SIMS measurement is shown in Fig. 2. Figure 3 shows the pixel area for infrared detection. Each pixel integrated in a thermopile-array detects the voltage-signal for the temperature difference between the thermally well isolated absorbing area and the cold pad of heat sink. The MEMS technology is also applied with selective surface-etching of GaAs substrate to AlGaAs lateral etch stop layer with the selective ratio over 200, to form the suspended diaphragm of pixel area and deposition process of absorber. The responsivity R is calculated by $R=\alpha\Sigma_N(S_pR_{thp} - S_nR_{thn})$. We use the absorption coefficient $\alpha=1$, the number of a couple of p- and n-piles N=8, $S_{p,n}$ is the Seebeck coefficient of p- and n-piles. The Seebeck effect consideration has been theoretically discussed in details [3]. The Seebeck coefficient $S=S_p-S_n=2{,}120$ µV/K, where $S_n=S_{0n}$(diffusion component)+S_{phn} (phonon-drag component) =-(850+20)=-870 µV/K, and $S_p=S_{0p}$(diffusion component)+S_{php} (phonon-drag component)= 1,200+50=1,250 µV/K [3]. The $R_{thp,n}$ is the thermal resistance of p- and n-piles, where the thermal resistivity W=9.2 for AlGaAs and 2.3K·cm/W for GaAs, respectively, the thickness of InGaAs channel layer d=10 nm, beam thickness t=0.34 for n-type and 0.55 µm for p-type pile, respectively. The mechanical stability of AlGaAs/InGaAs pile can be the same as that of poly-silicon pile [4]. The R is calculated to be 4,900 V/W, almost comparable with poly-Si [4]. The detectivity D* is calculated using $D^*=R(A\Delta f/(4k_BTR_{el}))^{1/2}$. We use the detection area $A=50\times50$ µm^2, the frequency band $\Delta f=1$ Hz, k_B the Boltzmann constant, the absolute temperature T=300K.

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The electric resistance of the total piles is R_{el} =35 kΩ, where we assume the carrier mobility of 8,000 for electron and 320 $cm^2/V \cdot s$ for hole, and the sheet carrier concentration $N_s = 1.2 \times 10^{12}$ cm^{-2} of 2DEG and/or 2DHG. The D* is calculated to be 2.0×10^9 $cmHz^{1/2}/W$, which is one order of magnitude higher than 10^8 $cmHz^{1/2}/W$ of VO_x-bolometer [5], while two orders of magnitudes lower than $10^{11} cmHz^{1/2}/W$ of cooled HgCdTe-based photodiode [6]. The response time is calculated to be 110 μs, two orders of magnitude higher speed than 10 ms of VO_x-bolometer [5] and 25 ms of poly Si thermopile [4], using $\tau = C\ R_{th,total}$ with heat capacitance of the detection area $C = 7.0 \times 10^{-9}$ J/K and the total thermal resistance $R_{th,total} = 1.5 \times 10^4$ K/W.

MEASURED RESULTS AND DISCUSSION: Black body measurements have been carried out directly without any filter, and with the band pass filter (14>λ>8 μm) under normal atmospheric pressure. The incident radiated power P_{in} into the pixel from the black body infrared radiator can be fitted to $P_{in} = V_{out}/R$.The relation of thermovoltage V_{out} versus black body radiation temperature T_b has been demonstrated as shown in Fig. 4. The measured plotted data (■and ▲) are at T_b=800-1,200K. As shown in the figure, the calibrated data (○, □ and △) are derived from the measured plotted data (■) without filter, multiplied by λT_b–integral rate [7] for λ>3 μm, λ>5 μm (Ge-window) and λ>8 μm, respectively. It is noted that the calibrated data (△) for λ>8 μm are close to the measured data (▲) with filter (14>λ>8 μm). The T_b dependence of V_{out} are also calculated, where R is assumed from 1,000 to 5,000 V/W, as a parameter. The calibrated data for λ>5 μm are close to R of 3,000 V/W. The measured value for R_{el} is 2.8 MΩ due to large contact resistance of p and n-electrodes in the fabrication process, larger than the designed value of 35 kΩ. Therefore the detectivity D* might be roughly estimated to be 1.4×10^8 $cmHz^{1/2}/W$, although D* has to be analyzed based on frequency dependence of noise spectrum measurement. In conclusion, these devices are expected to realize high performances due to superior Seebeck coefficient and the excellently high mobility of 2DEG and 2DHG in high purity channel layers at the heterojunction interface, and this technology demonstrates the low-cost potentiality for uncooled infrared FPA application.

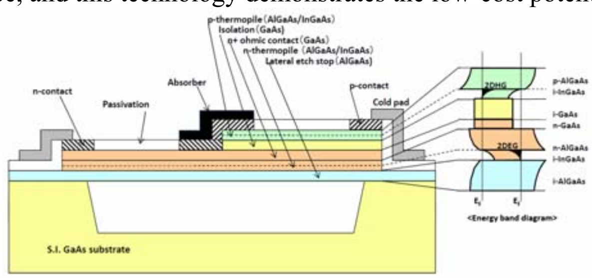


Fig.1 Cross sectional structure of AlGaAs/InGaAs H-PILE.

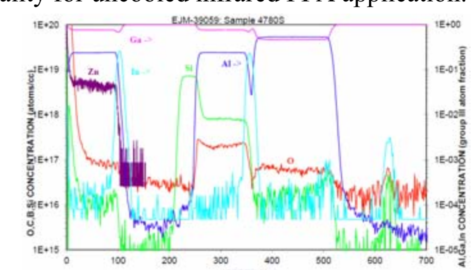
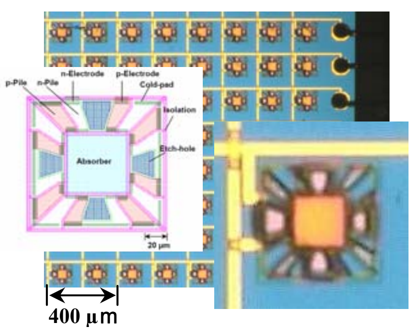


Fig. 2 Measured SIMS data for the stacked epitaxial structure.



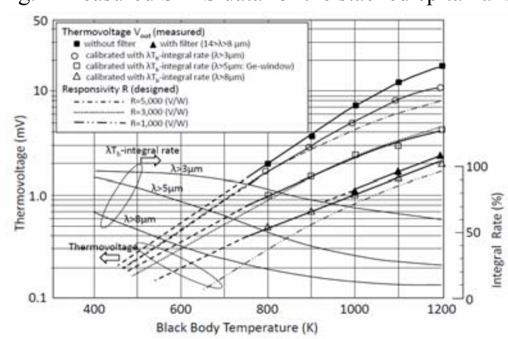


Fig. 3 Pixel pattern for infrared detection of 32x32 matrix array. Fig. 4 Thermovoltage and $\lambda\ T_b$-integral rate, vs. black body temp.

Keywords: Seebeck effect, heterostructure-thermopile, AlGaAs/InGaAs, HEMT, MEMS, FPA, infrared image sensor

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