Long-wavelength stacked SiGe/Si heterojunction internal photoemission infrared detectors using multiple SiGe/Si layers

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ABSTRACT

Utilizing low temperature silicon molecular beam epitaxy (MBE) growth, long-wavelength stacked SiGe/Si heterojunction internal photoemission (HIP) infrared detectors with multiple SiGe/Si layers have been fabricated and demonstrated. Using an elemental boron source, high doping concentration ($\approx 4 \times 10^{20}$ cm^{-3}) has been achieved and high crystalline quality multiple $Si_{0.7}Ge_{0.3}/Si$ layers have been obtained. The detector structure consists of several periods of degenerately boron doped ($\approx 4 \times 10^{20}$ cm^{-3}) thin (≤ 50 Å) $Si_{0.7}Ge_{0.3}$ layers and undoped thick (≈ 300 Å) Si layers. The multiple p^+-$Si_{0.7}Ge_{0.3}$/undoped-Si layers show strong infrared absorption in the long-wavelength regime mainly through free carrier absorption. The stacked $Si_{0.7}Ge_{0.3}/Si$ HIP detectors with $p = 4 \times 10^{20}$ cm-3 exhibit strong photoresponse at wavelengths ranging 2 to 20 μm with quantum efficiencies of about 4 **70** and 1.5 % at 10 and 15 μm wavelengths, respectively. The detectors show near ideal thermionic-emission limited dark current characteristics.

Long-wavelength infrared (LWIR) detectors and imaging systems are required for many space and defense applications. Especially, very long wavelength (13- 17 μm) imaging is needed for the current NASA's Earth Observing System (EOS). Recently, with the advent of the silicon molecular beam epitaxy (Si-MBE) growth technique, novel SiGe/Si heterojunction internal photoemission (HIP) IR detectors have been fabricated and demonstrated to exhibit tailorable detector response in the long-wavelength infrared regime [1-5]. Furthermore, using SiGe/Si HIP detector elements and monolithic CCD readout circuitry, 400 x 400 and 320 x 244 focal plane arrays with 10 μm cut-off wavelength were fabricated by Tsaur *et. al*, and high quality images were demonstrated [4,5]. The previously demonstrated SiGe/Si HIP detectors consist of a degenerately doped single p^+-SiGe layer as an emitter and a p-type Si substrate as a collector. The detection mechanism involves infrared absorption in the p^+-SiGe emitter layer mainly through free carrier absorption followed by the internal photoemission of photo-excited holes over the SiGe/Si heterojunction barrier into the Si substrate. The cut-off wavelength λ_c of the HIP detector is determined by the effective barrier height $q\Phi_b$ which is the energy difference between the $Si_{1-x}Ge_x$/Si valence band offset ΔE_v and the Fermi-level Ef in the SiGe layer (i.e., $q\Phi_b = \Delta E_v - Ef$). The valence band offset ΔE_v between strained $Si_{1-x}Ge_x$ and Si layers and the Fermi-1evel Ef can be tailored by changing the Ge composition and doping concentration in the SiGe layer, respectively. Thus, the cut-off wavelength can be tailored over a wide IR range (3- 30 μm) for SiGe/Si HIP IR detectors by engineering the Ge and doping concentrations of $Si_{1-x}Ge_x$ layer.

The external quantum efficiency (η) of HIP detectors is a product of absorption (A) in SiGe layers and internal quantum efficiency (η_i) which is defined as the ratio of the collected holes to the photo-excited holes, i.e., $\eta = A\,\eta_i$. The internal quantum efficiency of HIP detectors is limited by inelastic hole-hole and hole-phonon scattering as well as the number of holes redirected from the SiGe/air interface to the SiGe/Si interface. Reducing

the SiGe layer thickness enhances the internal quantum efficiency since photo-excited holes would suffer less inelastic scattering [6]; however, reducing the SiGe layer thickness reduces infrared absorption as well. Thus, the optimal SiGe layer thickness is determined by the trade-off between absorption and internal quantum efficiency. One way of achieving high internal quantum efficiency without losing absorption is by incorporating multiple thin absorbing SiGe layers which are stacked between Si barriers. The device structure and energy band diagram of a stacked SiGe/Si HIP detector are depicted in Figs. 1 (a) and (b), respectively. For this detector each individual layer has high η_i due to the thin SiGe layer and the absorption from each layer contributes to the total absorption. Furthermore, due to the applied electric field toward the Si substrate (z-direction), the photo-excited holes traveling opposite to z-direction will be redirected toward the Si substrate. This will further increase the internal quantum efficiency. A similar detector operating in 5-10 μm wavelength range was previously demonstrated by Park *et, al [7].*
In this letter, we demonstrate long-wavelength stacked $Si_{0.7}Ge_{0.3}/Si$ HIP detectors with 20 μm cut-off wavelength. The detectors show enhanced long-wavelength photoresponse, and near ideal thermionic-emission limited dark current characteristics.

The stacked layer SiGe/Si HIP detectors were fabricated by MBE growth of multiple p^+-$Si_{1-x}Ge_x$ and undoped-Si layers on oxide patterned p--type Si(100) wafers where n-type guard rings were incorporated at the periphery of the active detector area to minimize edge leakage current. Prior to MBE growth, a wafer was cleaned using the "spin-clean" method which involves the removal of a chemically grown protective oxide using an HF/ethanol solution in a nitrogen grove box [8]. Then, the wafer was loaded into a commercial Riber EVA 32 Si MBE system with a base pressure of 3 x 10-11 torr, and heated to 650 "C to desorb hydrogen adlayer. Ge and Si were evaporated from electron-gun sources, and elemental boron was evaporated from a high-temperature Knudsen cell. The growth temperature was maintained at 400" "C. The detectors were fabricated by standard Si processing steps which included plasma etching of MBE grown SiGe/Si layers and aluminum evaporation/patteming to make ohmic contacts on the top p^+-SiGe layer and boron implanted Si-p^+ wells as shown in Fig. l(a).

The infrared absorption of the multiple SiGe/Si layers at normal incidence was characterized with a Fourier transform infrared (FTIR) spectrometer. Figure 2 shows the absorption spectrum of a multiple SiGe/Si layer structure which consists of four periods of 50 Å-thick p^+-$Si_{0.7}Ge_{0.3}$ layers and 300 Å-thick undoped Si layers, The SiGe layers were boron doped to about 4 x1020 cm^{-3}. The absorption increases with wavelength, and strong absorption (30 to 45 %) is obtained beyond 10 μm. The infrared absorption is mainly due to the strong free carrier absorption caused by the heavy doping in the SiGe layers. The small peak near 3 μm is due to the intervalence-band transition [9, 10].

The photoresponse of the stacked HIP detectors was measured using a globar, a monochromator with several band pass filters to eliminate the higher order effects from gratings, and a pyroelectric detector to calibrate photon flux. The absolute quantum efficiency of the detectors was measured using a 1000 K blackbody source. Infrared illumination was applied on the front side of the detectors. Figure 3 shows the photoresponse spectra of a stacked HIP detector in terms of external quantum efficiency. The detector shown in this figure does not employ an anti-reflection coating nor an optical cavity. The detector consists of three 50 Å-thick p^+-$Si_{0.7}Ge_{0.3}$ layers which are separated by 300 Å-thick undoped Si layers. The boron concentration is 4 xl 0^{20} cm^{-3}. The active detector area is 1.25 x10-3 cm^{-2}, The operating temperature and bias voltage are 30 K and -0.5 V (positive to the top SiGe layer), respectively.

The detector shows broad photoresponse which cuts off at around 20 pm. The peak response lies at around 5 μm with 6 % external quantum efficiency. The response gradually decreases as the wavelength increases. The detector manifests about 4 % and 1.5 % external quantum efficiencies at 10 μm and 15 μm wavelengths, respectively. The observed bow shaped spectral response is due to the combined effects of absorption, which increases with wavelength increase, and internal quantum efficiency, which drops rapidly with wavelength increase. This stacked SiGe/Si HIP detector, in general, exhibits higher quantum efficiency in the LWIR regime ($\lambda > 10 \mu m$) than our previous single layer SiGe/Si HIP detectors with the same Ge concentration, doping concentration and SiGe layer thickness. For example, a 200 Å-thick $Si_{0.7}Ge_{0.3}/Si$ HIP detector with p = 4 x 10^{20} cm-3 showed quantum efficiencies of about 2 % at 10 μm and less than 1 % at 15 pm. This can be due to the enhancement of internal quantum efficiency for the stacked SiGe/Si HIP detector, especially in the long-wavelength regime where photo-excited holes have small kinetic energies to cross over a potential barrier. Figure 4 shows the bias dependent photoresponse of this stacked SiGe/Si HIP detector. The wavelength was fixed at 10 μm. With small reverse bias (O to -0.2 V), the quantum efficiency increases rapidly. While above -0.2 V bias it increases slowly, and finally it gets saturated above -1 V. The increase of photoresponse is due to the enhancement of internal quantum efficiency with the applied field,

The dark I-V characteristics of the stacked SiGe/Si HIP detectors were measured at several temperatures. Forward and reverse bias modes show asymmetric I-V characteristics, because a larger leakage current occurs under forward bias. Fig.5 (a) shows reverse-bias dark current characteristics of a stacked SiGe/Si HIP detector shown in Fig. 4. It shows the thermionic-emission limited dark I-V characteristics, especially near the detector operating bias voltage (-0.2 to -0.5 V). The measured I-V data at several different temperatures were further analyzed by activation energy analyses. For the stacked SiGe/Si HIP detectors, the thermionic-emission current can be also described by

$$J_o = A^{**} T^2 \exp(-q\Phi_b/kT)$$

where A^{**} is the Richardson constant, T is the absolute temperature,' k is Boltzmann constant, and $q\Phi_b$ is effective barrier height. The above equation is derived for the three-dimensional thermionic-emission case, but the equation can still be applied to the present stacked SiGe/Si HIP detectors, in spite of possible subband formation inside SiGe layers due to the thin SiGe layers sandwiched between Si potential barriers. This is because subbands are occupied up to considerably high energy states due to large Fermi-level energy (150 meV) in SiGe layers caused by degenerate doping, Figure 5(b) shows the activation energy plot for the stacked HIP detector shown in Fig.5(a) at -0.2 V bias voltage. The effective barrier height determined from the linear slope is 58 meV which corresponds to 21 μm cut off wavelength; and A^{**} determined from the ordinate intercept at $1/kT = O$ is 16 $A/cm^2/K^2$. This estimated barrier height agrees well with the observed cut-off wavelength which was shown in Fig. 4. The small A^{**} values indicates that the epitaxial layer quality of multiple SiGe/Si layers is excellent. The activation analyses suggest that the detector dark current is limited by the ideal thermionic-emission current.

In summary, we have demonstrated stacked SiGe/Si HIP infrared detectors using multiple $Si_{0.7}Ge_{0.3}/Si$ layers. High crystalline quality multiple p^+-$Si_{0.7}Ge_{0.3}/p^-$-Si layers were grown by low temperature MBE incorporating elemental boron source for doping. This stacked HIP detector showed enhanced photoresponse, especially at the long-wavelength regime as compared to single layer SiGe/Si HIP detectors. This may be due to the enhanced internal quantum efficiency. The detector showed broad photoresponse at the wavelength between 2 to 20 μm with external quantum efficiencies of about 4910 and 1.5 % at 10 and 15 μm wavelengths, respectively. The dark current characteristics were measured at several temperatures and analyzed by activation energy analyses. The analyses suggested that the detector dark current was limited by the near ideal thermionic-emission current.

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FIGURE CAPTIONS

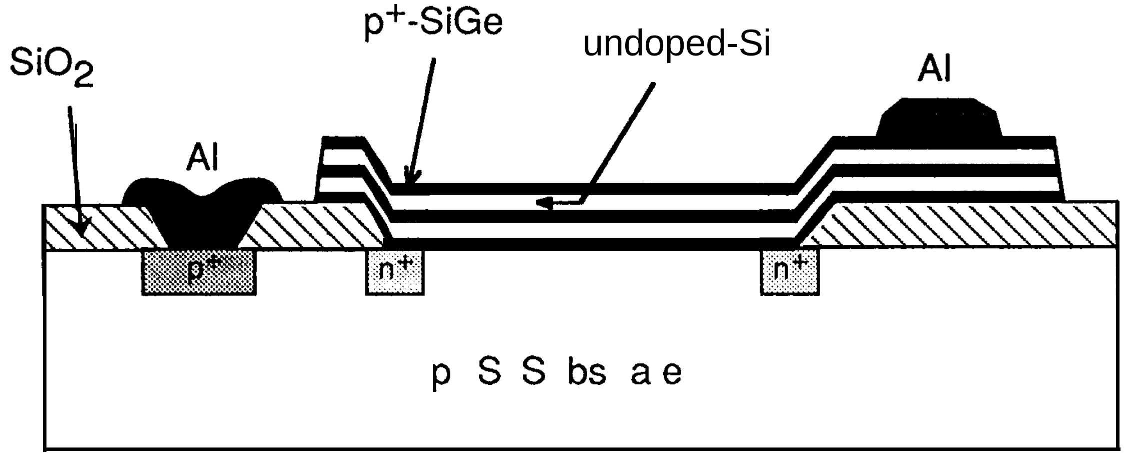
Fig. l.(a) Schematic cross section ofastacked SiGe/Si HIP detector. (b) Energy band diagram of a stacked SiGe/Si HIP structure showing the detection mechanism.

Fig. 2. FTIR absorption spectra of multiple SiGe/Si layers with four periods of 50 Å p^+-$Si_{0.7}Ge_{0.3}$ /300 Å undoped Si layers. Boron doping is about 4 x 10^{20} cm^{-3}. It exhibits strong free carrier absorption.

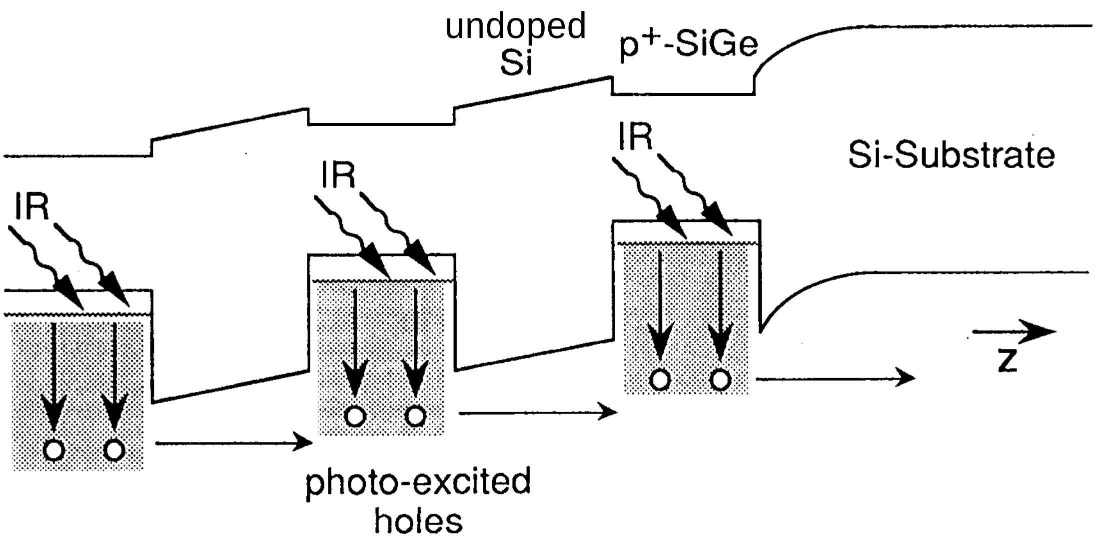
Fig. **3,** External quantum efficiency vs. wavelength for a stacked $Si_{0.7}Ge_{0.3}$/Si HIP detector. The detector consists of three 50 Å-thick p^+-$Si_{0.7}Ge_{0.3}$ layers which are separated by 300 Å-thick undoped Si layers. The boron concentration for the detectors is about 4 x 10^{20} cm^{-3}.

Fig. **4,** The reverse bias dependent photoresponse of the stacked $Si_{0.7}Ge_{0.3}$/Si HIP detector shown in Fig, 3 at the fixed wavelength of 10 μm.

Fig. **5.** (a) The reverse bias current-voltage (J-V) characteristics of a stacked SiGe/Si stacked HIP detector shown in Fig. 3 and (b) the activation energy plots for this detector at -0.2 V bias.


p+-SiGe
undoped-Si
SiO2
Al
Al
p+
n+
n+
p S S bs a e

(a)


undoped
Si
p+-SiGe
Si-Substrate
IR
IR
IR
z
photo-excited
holes

(b)

Fig. 1

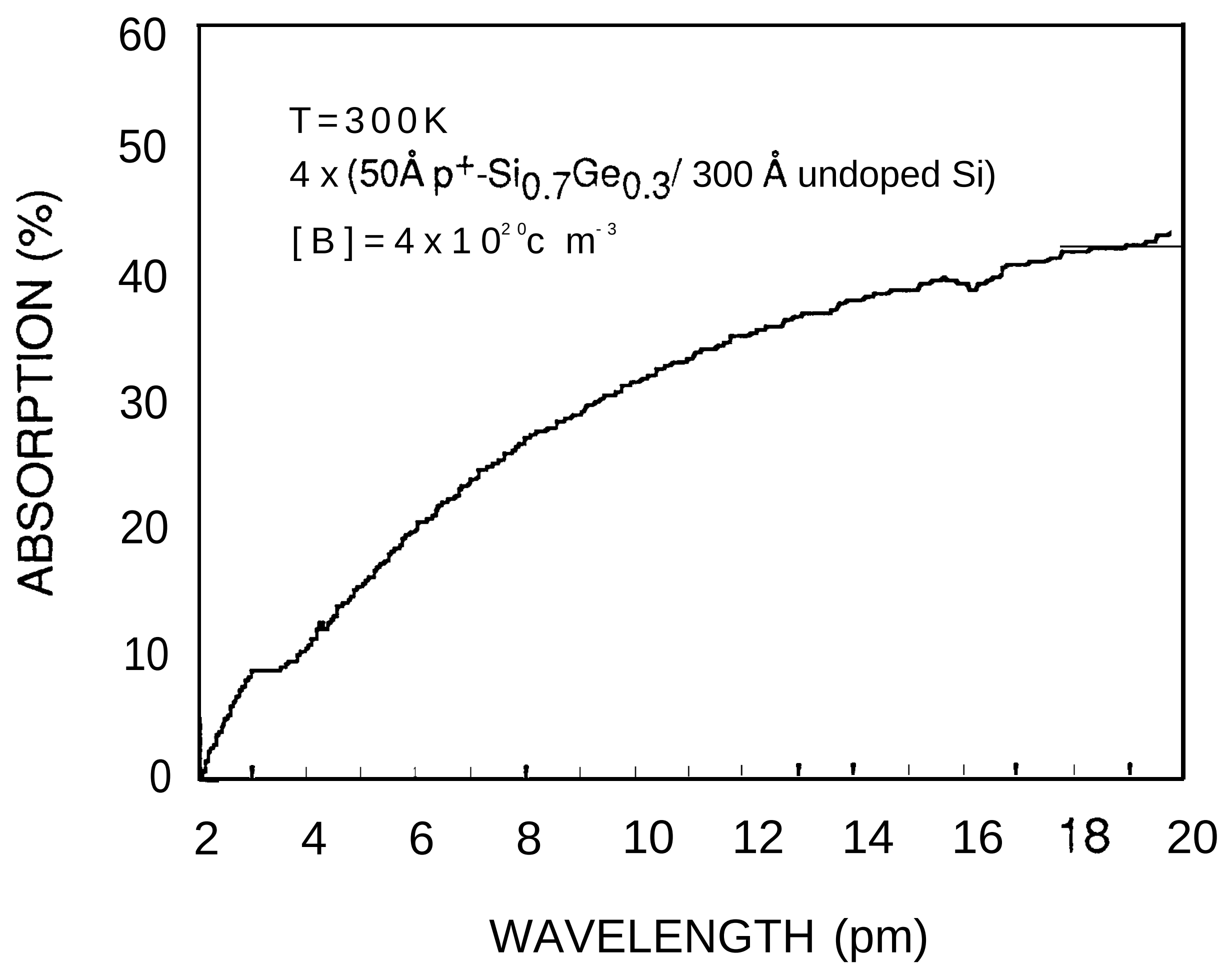

T = 300 K
4 x (50Å p+-Si0.7Ge0.3/ 300 Å undoped Si)
[B] = 4 x 10^20 cm^-3
ABSORPTION (%)
0
10
20
30
40
50
60
2
4
6
8
10
12
14
16
18
20
WAVELENGTH (pm)

Fig. 2

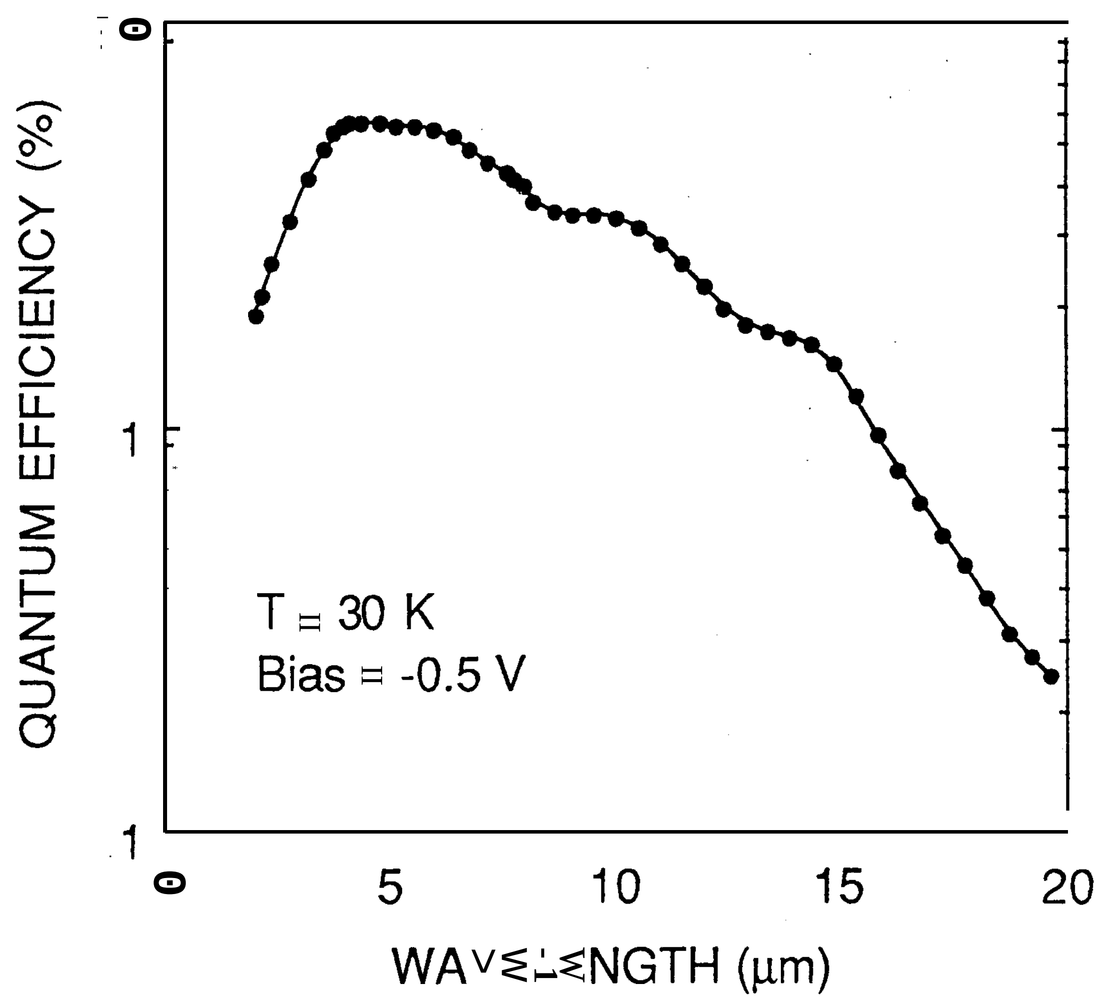
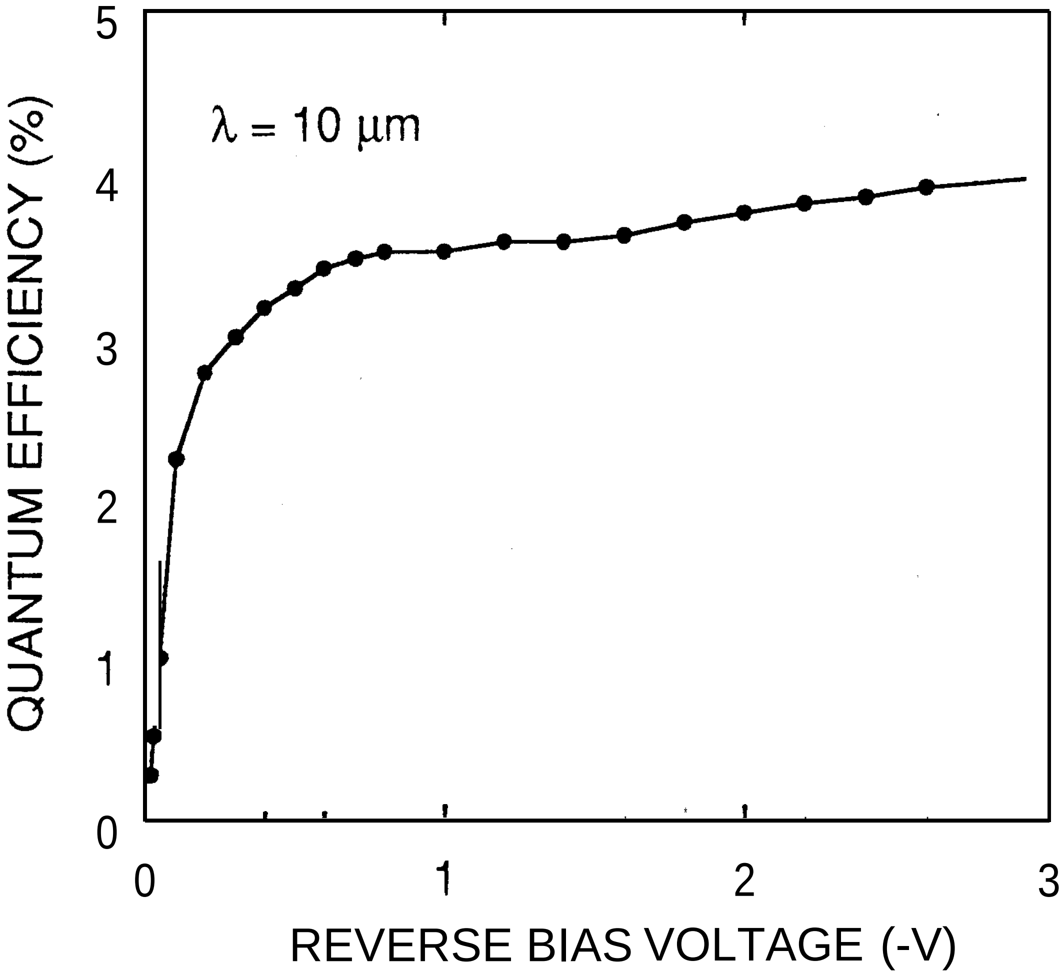

QUANTUM EFFICIENCY (%)
0
1
.1
0
5
10
15
20
WAVELENGTH (μm)
T = 30 K
Bias = -0.5 V

Fig. 3



5
4
3
2
1
0
QUANTUM EFFICIENCY (%)
λ = 10 μm
0
1
2
3
REVERSE BIAS VOLTAGE (-V)

Fig. 4

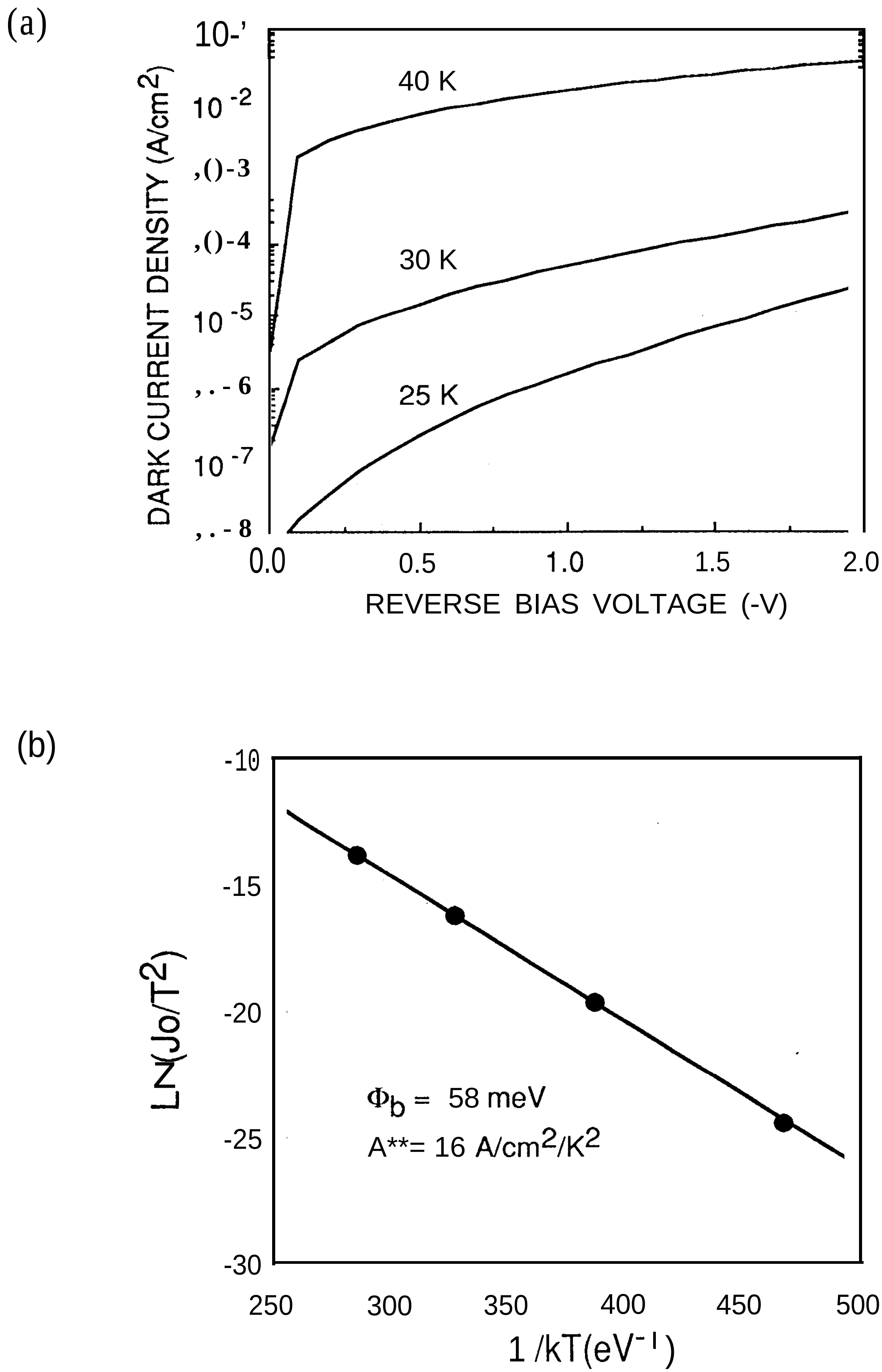

(a)
40 K
30 K
25 K
DARK CURRENT DENSITY (A/cm2)
REVERSE BIAS VOLTAGE (-V)
0.0
0.5
1.0
1.5
2.0
(b)
LN(Jo/T2)
1 /kT(eV-1)
Φb = 58 meV
A**= 16 A/cm2/K2
-10
-15
-20
-25
-30
250
300
350
400
450
500

Fig. 5