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Novel $Si_{1-x}Ge_x$/Si Heterojunction Internal Photoemission Long Wavelength Infrared Detectors

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ABSTRACT

There is a major need for long-wavelength-infrared (LWIR) detector arrays in the range of 8 to 16 μm which operate with close-cycle cryocoolers above 65 K. In addition, it would be very attractive to have Si-based infrared (IR) detectors that can be easily integrated with Si readout circuitry and have good pixel-to-pixel uniformity, which is critical for focal plane array (FPA) applications. We report here a novel $Si_{1-x}Ge_x$/Si heterojunction internal photoemission (HIP) detector approach with a tailorable LWIR cutoff wavelength, based on internal photoemission over the $Si_{1-x}Ge_x$/Si heterojunction. The HIP detectors were grown by molecular beam epitaxy (MBE), which allows one to optimize the device structure with precise control of doping profiles, layer thickness and composition.

The HIP detector incorporates a degenerately doped p^+-$Si_{1-x}Ge_x$ layer as the photo emitter, and the Si substrate as the collector. The detection mechanism is IR absorption in the p^+-$Si_{1-x}Ge_x$ emitter followed by internal photoemission of photoexcited holes over the $Si_{1-x}Ge_x$/Si heterojunction barrier into the p-Si substrate. The valence band discontinuity between $Si_{1-x}Ge_x$ and Si layers determines the energy barrier, and can be adjusted by varying the Ge composition ratio x. Thus, the cutoff wavelength of the $Si_{1-x}Ge_x$/Si HIP IR detector is tailorable over a wide LWIR range; for example, 8 -16 μm with x ranging from about 0.2 to 0.4. The tailorable cutoff wavelength can be used to optimize the trade-off between the LWIR response and the cooling requirements of the detector.

The $Si_{1-x}Ge_x$/Si HIP detector approach is made possible by the recent advance in MBE growth of degenerately doped p^+-$Si_{1-x}Ge_x$ layers with abrupt boron doping profiles. Doping concentrations to 10^{20} cm^{-3} in the $Si_{1-x}Ge_x$ layers are achieved using boron from an HBO_2 source during MBE growth. The p^+ doping enables adequate IR absorption for photoexcited hole generation in the $Si_{1-x}Ge_x$ layers.

Compared to silicide Schottky-barrier detectors, the HIP detector offers a higher internal quantum efficiency (QE). One reason is the narrow band of hole occupied states in the p^+-$Si_{1-x}Ge_x$ layer due to its semiconductor band structure. In Schottky detectors, photons can excite carriers from states far below the Fermi energy such that they do not gain sufficient energy to overcome the barrier. Near threshold only a small fraction of the photoexcited carriers can exceed

the barrier energy. Consequently, its QE rises only slowly with energy above the barrier cutoff energy. In contrast, the narrow band of absorbing states in the HIP detector leads to a sharper turn-on, which in turn results in useful sensitivities close to the cutoff. This property avoids a serious weakness of Schottky detectors where the Fowler's dependence provides reasonable QE only at wavelengths well below the cutoff, which requires lower operating temperatures for a given dark current. Another reason is that photoexcited holes traveling over the potential barrier can more easily conserve their lateral momentum because of the more favorable ratio of effective masses across the heterojunction. Furthermore, improvement is expected because of reduced inelastic hole scattering in the $Si_{1-x}Ge_x$ layers compared with the silicides, and the ability to grow $Si_{1-x}Ge_x$ layers with optimal thickness, doping and composition.

Preliminary HIP detectors have been fabricated by MBE growth of $Si_{1-x}Ge_x$ layers with x = 0.2, 0.3 and 0.4 on patterned p-type Si substrates. The detectors incorporate n-type guard-rings defining the periphery of the active device areas to suppress leakage current. The photoresponses of the detectors were measured with front-side illumination using a blackbody source at 940 K. Photoresponses at wavelength 2 to 10 μm are obtained with QE above ~ 1% in these non-optimized structures. The tailorable cutoff wavelength of the proposed HIP detector has also been demonstrated by varying the Ge ratio x in the $Si_{1-x}Ge_x$ layers. The photoresponses of $Si_{1-x}Ge_x/Si$ HIP detectors with x = 0.2, 0.3 and 0.4 increase and extend to longer wavelengths as the Ge ratio x reduces from 0.4 to 0.2. Furthermore, the QE of the device can be improved by optimizing the layer thickness and the doping profile of the $Si_{1-x}Ge_x$ layers. By reducing the thickness of $Si_{0.7}Ge_{0.3}$ layers from 400 nm to 40 nm, and increasing the boron doping concentrations from 10^{19} to 10^{20} cm^{-3}, the QE's have been improved by two orders of magnitude (from 0.003 % to ~0.3% at 8 μm).

In conclusion, the feasibility of a novel $Si_{1-x}Ge_x/Si$ HIP detector has been demonstrated with tailorable cutoff wavelength in the LWIR region. Photoresponse at wavelengths 2 to 10 μm are obtained with QE above ~ 1% in these non-optimized device structures. It should be possible to significantly improve the QE of the HIP detectors by optimizing the thickness, composition, and doping concentration of the $Si_{1-x}Ge_x$ layers and by configuring the detector for maximum absorption such as the use of a cavity structure. With optimization of the QE and by matching the barrier energy to the desired wavelength cutoff to minimize the thermionic current, we predict near background limited performance in the LWIR region with operating temperatures above 65K. Finally, with mature Si processing, our relatively simple device structure offers potential for low-cost producible arrays with excellent uniformity.

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$Si_{1-x}Ge_x$ /Si Heterojunction Internal Photoemission Detectors for LWIR Focal Plane Array Applications

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OUTLINE

- Introduction
- Advantages of the $Si_{1-x}Ge_x$ HIP detectors
- Growth and Fabrication of the HIP detectors
- Results and Discussion
- Summary

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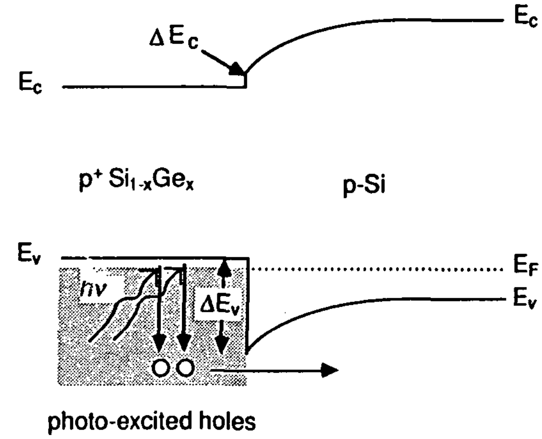
INTRODUCTION

Novelties

- Degenerately doped p^+-$Si_{1-x}Ge_x$ layers for strong IR absorption
- $Si_{1-x}Ge_x$/Si valence band offset as the potential barrier, which is tailorable over a wide LWIR range

Detection mechanism

- IR absorption in the p^+-$Si_{1-x}Ge_x$ layers
- Internal photoemission over the heterojunction barrier



Band Structure of $Si_{1-x}Ge_x$ /Si Heterojunction Internal Photoemission (HIP) IR Detectors

IR Absorption in Degenerately Doped P+ $Si_{1-x}Ge_x$ Layers

- Degenerately doped p^+-$Si_{1-x}Ge_x$ layers are required for strong IR absorption for photoexcited hole generation.
- Two IR absorption mechanisms
  - Free-carrier absorption

$$\alpha_f = \frac{Nq^2\lambda^2}{m^* 8\pi^2 n c^3 \tau} \sim N^{1.5}\,\lambda^{1.5\text{-}3.5}$$

  - Intra-valence-band transition

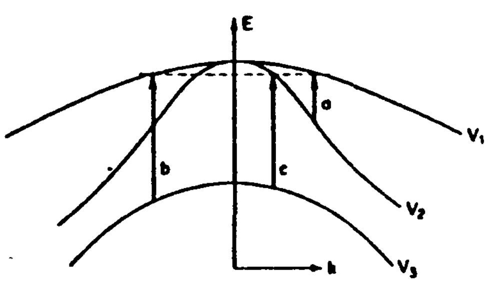
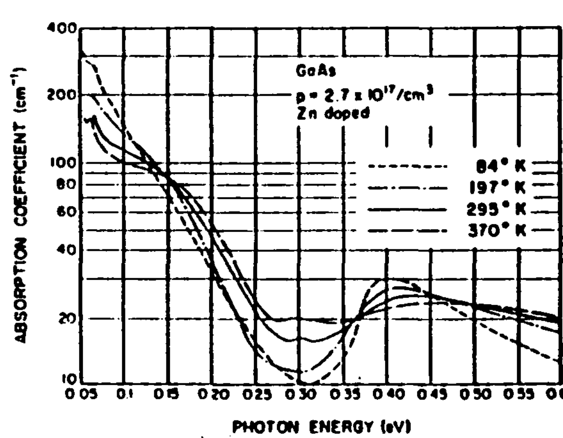


Fig. 3-34 Valence subband structure and intraband transitions.



IR absorption increases with carrier concentration and photon wavelength

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Low Temperature Boron Doping for P+ $Si_{1-x}Ge_x$ Layers

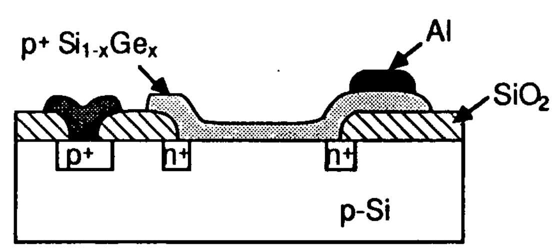
The $Si_{1-x}Ge_x$ /Si HIP detector approach is made possible by utilizing a low temperature boron doping technique developed at JPL.

Low growth temperatures required
- 2-dimensional (planar) $Si_{1-x}Ge_x$ growth
- Abrupt boron doping profiles

[B] > 10^{20} cm^{-3} has been achieved using boron from an HBO_2 source during MBE growth

Advantages of $Si_{1-x}Ge_x$ /Si HIP LWIR Detectors

- Si-based IR detector with similar advantages of Schottky-barrier IR detectors:
  - Integration with Si readout circuitry either monolithically or by In bond bounding
  - Good pixel-to-pixel uniformity
  - Allows normal IR illumination
  - High yield and low cost (cents/pixel)



Device structure of $Si_{1-x}Ge_x$/Si HIP LWIR detectors

- Feasible for large focal plane array application as demonstrated by commercially available 512x512 PtSi arrays, but extended to the LWIR regime

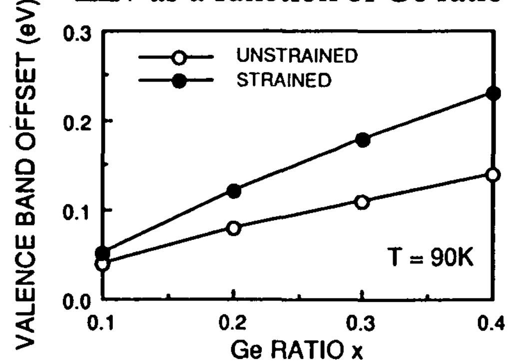
- Tailorable LWIR Cutoff
  - can be adjusted to match the desirable cutoff to minimize the dark current

- Relatively good QE's for large array applications

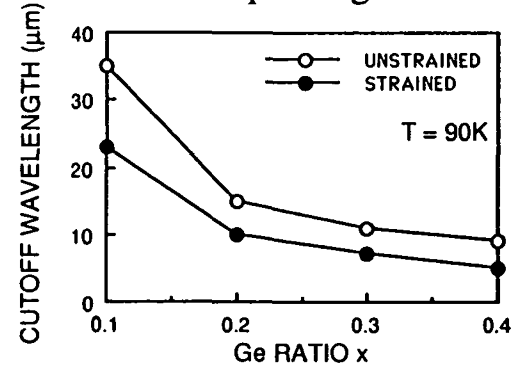
Tailorable Cutoff in LWIR Regime

- The cutoff wavelength λc of the $Si_{1-x}Ge_x/Si$ HIP detector is determined by the valence band offset ΔEv between $Si_{1-x}Ge_x$ and Si, which is equal to ~ 90% of the bandgap difference between $Si_{1-x}Ge_x$ and Si. The bandgap of $Si_{1-x}Ge_x$ can be varied by adjusting Ge ratio x and strain. Consequently, the cutoff wavelength of $Si_{1-x}Ge_x$ /Si HIP detector is tailorable in a wide LWIR region.

ΔEv as a function of Ge ratio x

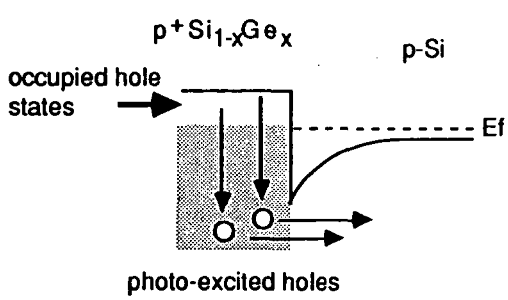


The corresponding cutoff λc

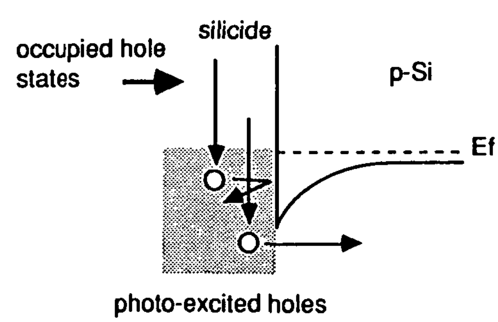


Higher QE (compared with Schottky detectors)

- Narrow band of occupied hole states (due to its semiconductor band structure) in the p^+-$Si_{1-x}Ge_x$ layer of the HIP detector leads to a sharper turn-on, resulting in useful sensitivities close to the cutoff



$Si_{1-x}Ge_x/Si$ HIP detectors



Silicide Schottky detectors

- The more favorable ratio of effective masses across the heterojunction reduces the backscattering of photoexcited holes

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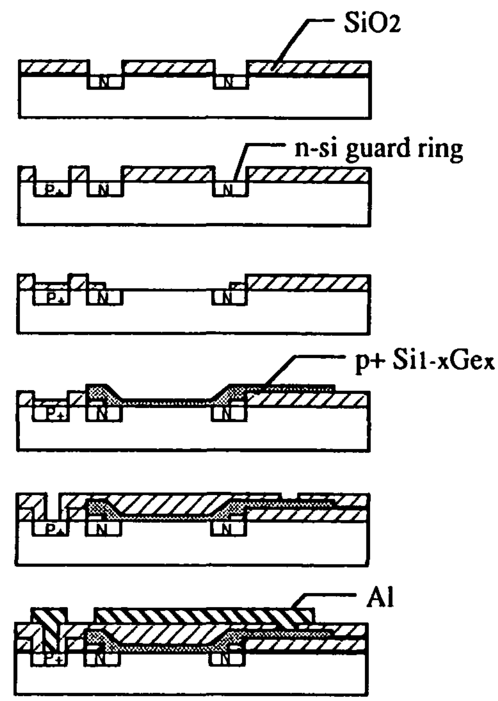
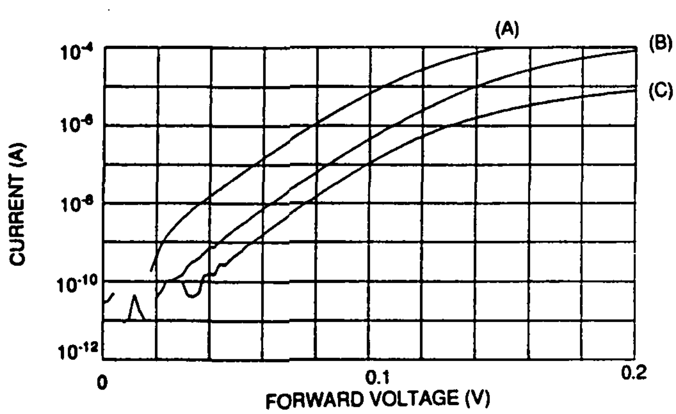
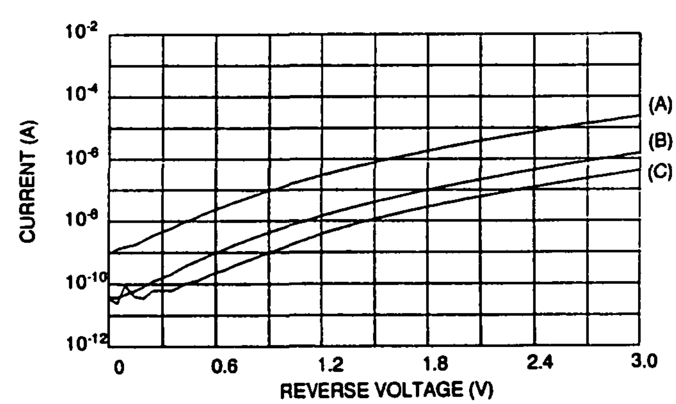
Fabrication of $Si_{1-x}Ge_x$/Si HIP IR Detectors

- Surface preparation : using "spin-clean" technique
- MBE growth of p^+-$Si_{1-x}Ge_x$ layers on patterned p-type Si(100) wafers
  Growth temperature = 600°C
  [B] = 10^{19} to 10^{20} cm^{-3}
  Ge ratio x = 0.2, 0.3 and 0.4
- Device fabrication
  Six level mask set
  In-house fabrication



Current-Voltage Characteristic





400 nm thick $Si_{0.72}Ge_{0.28}$ layers, [B] = 10^{19} cm^{-3}
Temp = 77 K
Bias applied to p-Si substrate, with the $Si_{0.72}Ge_{0.28}$ layer grounded
Ideality factor n =1.4, $J_o \sim 2 \times 10^{-6}$ Acm^{-2}

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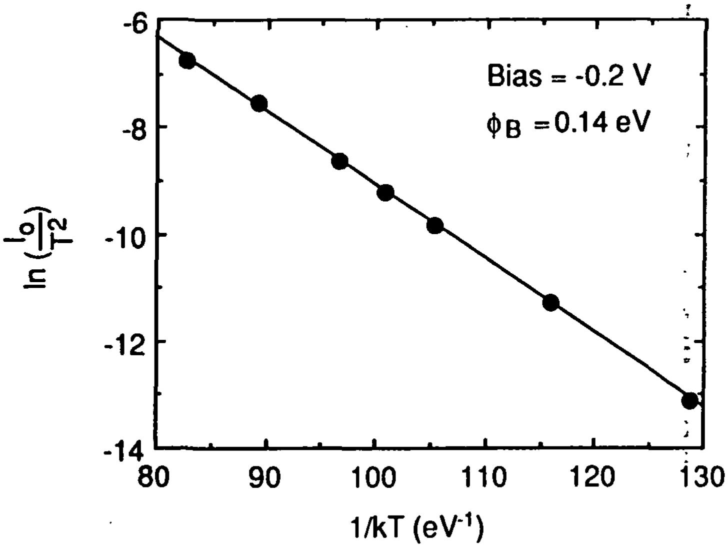
Activation Energy Measurement



400 nm thick $Si_{0.72}Ge_{0.28}$

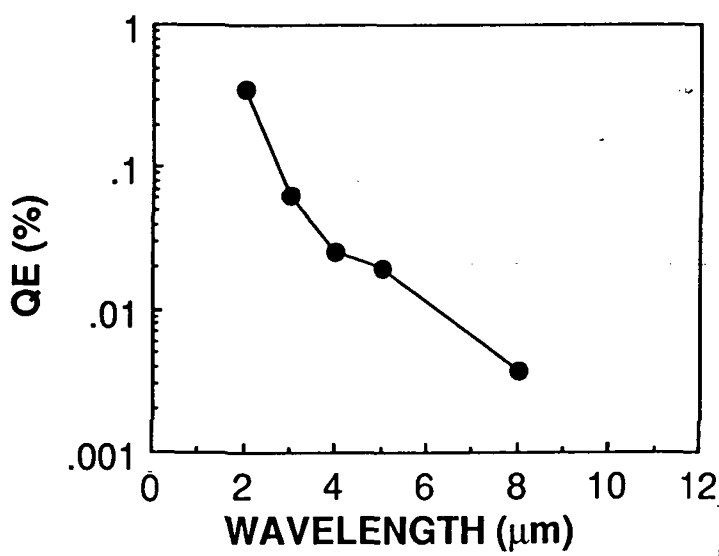
$[B] = 10^{19}\ cm^{-3}$

Temp = 90 -145 K

$$J_o = A^*\ T^2 \exp\left(-\frac{q\phi_B}{kT}\right)$$

$$\ln\left(\frac{J_o}{T^2}\right) = -\frac{q\phi_B}{kT} + \ln(A^*)$$

PHOTORESPONSE MEASUREMENTS



- 400 nm thick $Si_{0.72}Ge_{0.28}$
- $[B] = 10^{19}\ cm^{-3}$
- -1.5 V bias
- 77K measurement

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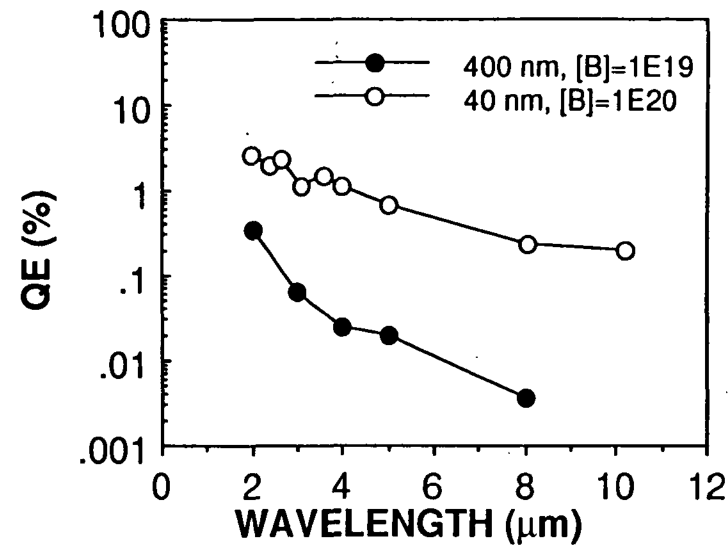
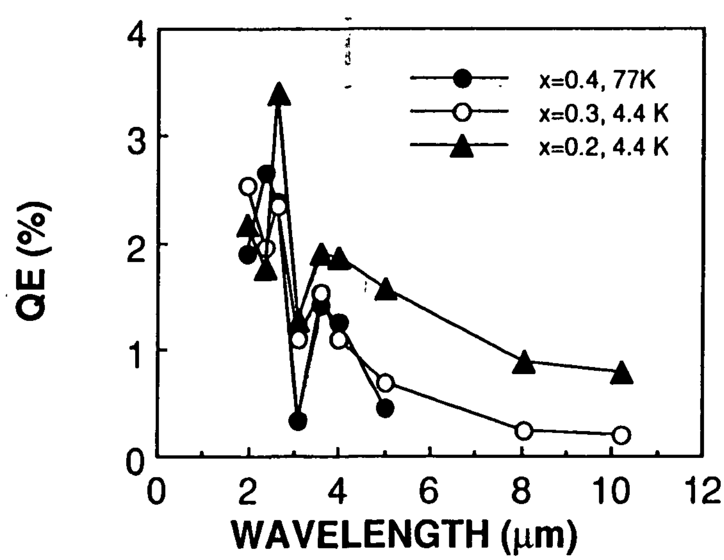
Optimization of Device Structure



- Two orders of magnitude QE improvement (from 0.003% to 0.3% at 8 μm) by reducing the thickness from 400 to 40 nm, and increasing [B] from 10^{19} to 10^{20} cm^{-3}
- Extended photoresponse as Ef moves further below Ev for degenerately doped p^+-$Si_{1-x}Ge_x$ layers

Tailorable LWIR Cutoff Wavelengths



- 40-nm-thick p^+-$Si_{1-x}Ge_x$ layers
- x = 0.2, 0.3 and 0.4
- [B] = 10^{20} cm^{-3}

- Photoresponse extends to longer wavelengths as Ge ratio x decreases
- QE increases as Ge ratio x decreases
- Demonstrated photoresponse improvement by optimizing the thickness, doping concentration and composition of the $Si_{1-x}Ge_x$ layers

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Discussion

NEΔT: Noise Equivalent Temperature change $NE\Delta T$ (the minimum ΔT required to have S/N=1) is the array figure of merit

- Uniformity-limited NEΔT

$$NE\Delta T_u = 7 \times 10^{-5}\, T^2 \lambda U$$

NEΔT = 60 mK for U= 0.1%, T= 293 K, and λ= 10 μm

- Single-pixel-limited NEΔT

$$NE\Delta T = \frac{(A\Delta f)^{1/2}}{D^* \,(dP_B/dT)\, \sin^2(\theta/2)}$$

For D* = 10^{10} cmHz$^{1/2}$/W, NEΔT = 10 mK for 50 μm square pixel, Δf =60 Hz, and f/2 optics.

For NEΔT (pixel) < 60 mK, D* > 1.6 x 10^9 cmHz$^{1/2}$/W

- Detectivity D* is given by

$$D^* = 0.4\, \eta\lambda\, (qJ_o)^{-0.5}$$

For $Si_{1-x}Ge_x$ /Si HIP detectors with an 11μm cutoff and η = 0.3% at 10 μm operating at 65 K (J_o = 2 x 10^{-4} Acm^{-2}), D* = 2 x 10^9 cmHz$^{1/2}$/W

Summary

- A new p^+-$Si_{1-x}Ge_x$/p-Si HIP detector approach has been demonstrated at wavelengths ranging from 2 to 10 μm with > 1% QE's.
- Cutoff is tailorable over a wide LWIR range by varying the Ge ratio x in the $Si_{1-x}Ge_x$ layers.
- Initial improvement of detector performance has been demonstrated by optimizing the thickness, doping concentration and composition of the $Si_{1-x}Ge_x$ layers.
- The potential detector performance (D* ~ 2 x 10^9 cmHz$^{1/2}$/W, at 65K) allows the fabrication of large LWIR FPA's with uniformity-limited performance (assuming 0.1% uniformity).
- Potential for low cost and producible large focal plane array fabrication with mature silicon processing and our relatively simple device structure.