A novel electron tunneling infrared detector

T.W. Kenny, S.B. Waltman, J.K. Reynolds, and W.J. Kaiser
Center for Space Microelectronics Technology
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91109

All thermal detectors of infrared radiation include the following components: An absorber of infrared radiation converts the incoming photons to heat, producing a temperature rise in the detector. A thermo-electric transducer converts the change in the temperature of the detector to an electrical signal. The detector is connected to a temperature reference by a finite thermal conductance, G. Given the efficiency of the infrared absorber, the temperature coefficient of the thermo-electric transducer, the thermal conductance to the temperature reference and the heat capacity of the detector, the performance of the device may be fully characterized. Useful thermal detectors require the existence of sensitive thermo-electric transducers that operate at the required temperature with low heat capacity. If the sensitivity of the transducer is high enough, the performance of the detector is limited by thermal fluctuations, for which the Noise Equivalent Power (NEP) is given by $\sqrt{4kT^2G}$.

The pneumatic infrared detector, originally developed by Golay in the late 1940s, uses the thermal expansion of one cm^3 of xenon at room temperature to detect the heat deposited by infrared radiation. This detector was limited by thermal fluctuations within a 10 Hz bandwidth, but suffered from long thermal time constants and a fragile structure. Nevertheless, it represents the most sensitive room temperature detector currently available in the LWIR. Fabrication of this type of detector on smaller scales has been limited by the lack of a suitably sensitive transducer.

We have designed a detector based on this principle, but which is constructed entirely from micromachined silicon, and uses a vacuum tunneling transducer to detect the expansion of the trapped gas. Because this detector is fabricated using micromachining techniques, miniaturization and integration into one and two-dimensional arrays is feasible. The extreme sensitivity of vacuum tunneling to changes in electrode separation will allow a prototype of this detector to operate in the limit of thermal fluctuations over a 10 kHz bandwidth. A calculation of the predicted response and noise of the prototype is presented within the general formalism of thermal detectors. Although the prototype electron tunneling infrared detector has not been designed to optimize the sensitivity, it should feature an NEP as low as 6×10^{-11} W/$\sqrt{\text{Hz}}$ for a 1 mm^2 active area while operating at room temperature. Some design changes that will allow reductions in the NEP by as much as another order of magnitude for a 1 mm^2 area will be discussed. The dependence of the characteristics upon the area of the detector will also be discussed.

At present, most of the components of the prototype have been fabricated and tested independently. In particular, a characterization of the micromachined electron tunneling transducer has been carried out. The measured noise in the tunnel current is within a decade of the limit imposed by shot noise, and well below the requirements for the operation of an infrared detector with the predicted sensitivity. Assembly and characterization of the prototype infrared detector will be carried out promptly.

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A Novel Electron Tunneling Infrared Detector

T.W. Kenny, S. B. Waltman, J.K. Reynolds, and W.J. Kaiser

Center for Space Microelectronics Technology
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91109

- **General Considerations**
- **Electron Tunneling Thermo-electric Transducer**
- **Design and Analysis**
- **Conclusions**

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IR Detector Classification

Quantum Detectors

- Incoming photons are converted to excited carriers in a semiconducting structure.
- The carriers propagate ballistically over barriers in the band structure and are counted. The barriers block the thermally generated carriers.

Thermal Detectors

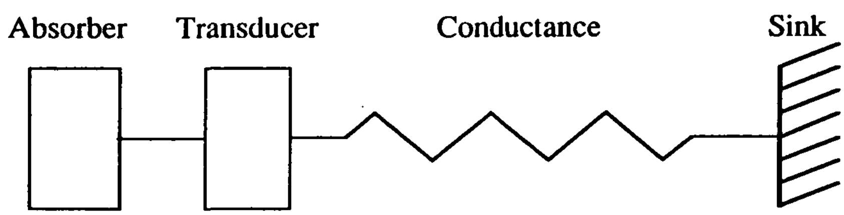
- Incoming photons are converted to heat.
- The heat is detected by a change in temperature of a thermally sensitive element.

Thermal Infrared Detector Requirements

- Infrared Absorber
  Converts incoming radiation to heat.
  Should have low heat capacity and high efficiency.

- Thermo-Electric Transducer
  Converts change in temperature to electrical signal.
  Should have low heat capacity and high conversion coefficient.

- Thermal Conductance
  Connects detector to temperature reference.
  Usually used to provide mechanical support and electrical contact.



Existing Thermal Detectors

- Bolometers
  Use temperature-dependent resistance of semiconductor or superconductor as thermo-electric transducer.
  Limited by availability of large resistance variations.
  State of the art detector for $\lambda > 100\ \mu m$.

- Pyroelectrics and Thermoelectrics
  Use temperature-dependent potential which occurs due to pyroelectric or thermoelectric effect.
  Difficult to fabricate with low heat capacity and thermal conductance.
  Most convenient technology for room-temperature detection in the LWIR.

- Pneumatics
  Use thermal expansion of gas at STP coupled with mechano-electrical transducer. Requires production of thin, flexible membrane.
  Small detectors limited by transducer sensitivity.
  Most sensitive room-temperature detector in the LWIR.

Improving the Pneumatic Infrared Detector

Use silicon micromachining to fabricate sensor components.

- Photolithographic techniques allow μm-scale precision.
- Use single crystals of silicon as raw material.
- Free-standing silicon oxy-nitride membranes may be used.
- Miniaturization of sensor components to less than 100 μm.
- Eventual integration of sensor and electronics possible.

Problem:

As the area of the pneumatic detector is reduced, the capacitive transducer becomes less sensitive.

Solution:

Find a more sensitive transducer technology.

Electron Tunneling

- In the early 1980 s, Binnig and Rohrer at IBM invented a new technique, Scanning Tunneling Microscopy (STM), for studying the structure of surfaces with atomic-scale resolution.

- In STM, a 'Tip' is positioned several Angstroms above the surface of interest. With the application of a voltage bias between the tip and the surface, a small tunneling current is observed.

- According to Quantum Mechanics, the probability for tunneling of individual electrons across the barrier depends exponentially on the thickness of the barrier, which is the separation between the electrodes in this case.

- For the conditions common to STM experiments, the tunnel current varies by an order of magnitude for each Å change in the electrode separation.

- This extreme sensitivity to changes in separation could be useful in an electro-mechanical transducer.

Transducer Sensitivity Comparison

Capacitive Motion Transducer

- Active area : 10 µm x 10 µm — Separation : 1 µm
- Voltage : 1 Volt — Capacitance : 0.88 fF
- Frequency : 200 kHz — Current : 1.1 nA

1 % change in current represents a **90 Å** change in separation.

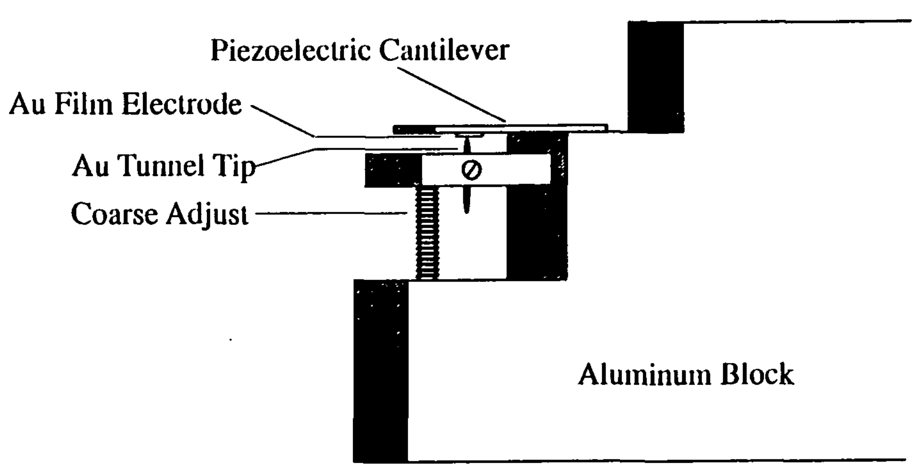
Electron Tunneling Motion Transducer

- Active area : 10 Å x 10 Å — Separation : 5 Å
- Voltage : 100 mV — Current : 1 nA
- Frequency : 10 Hz - 10 kHz

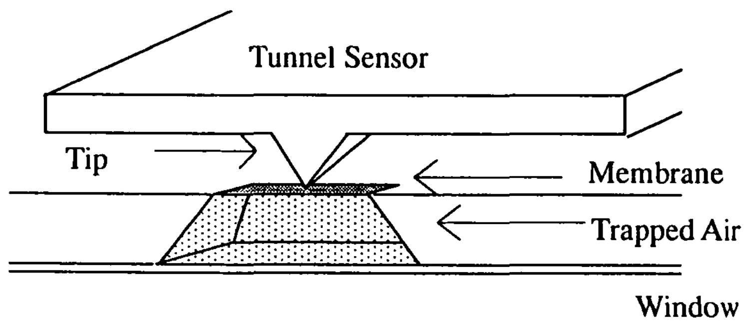
1 % change in current represents a **0.004 Å** change in separation.

Prototype Tunnel Sensor

- Piezoelectric Bimorph as actuator.
- Rigid mechanical structure.



Design of the Micromachined Infrared Tunnel Sensor



- Air-filled cavity bounded on one side by 0.5 μm silicon oxy-nitride membrane.
- 80 Å Au film used as IR Absorber and tunneling electrode.
- Folded silicon cantilever spring with integral tip.
- Electrostatic deflection used to control electrode separation.

Design Parameters for the Prototype Infrared Tunnel Sensor

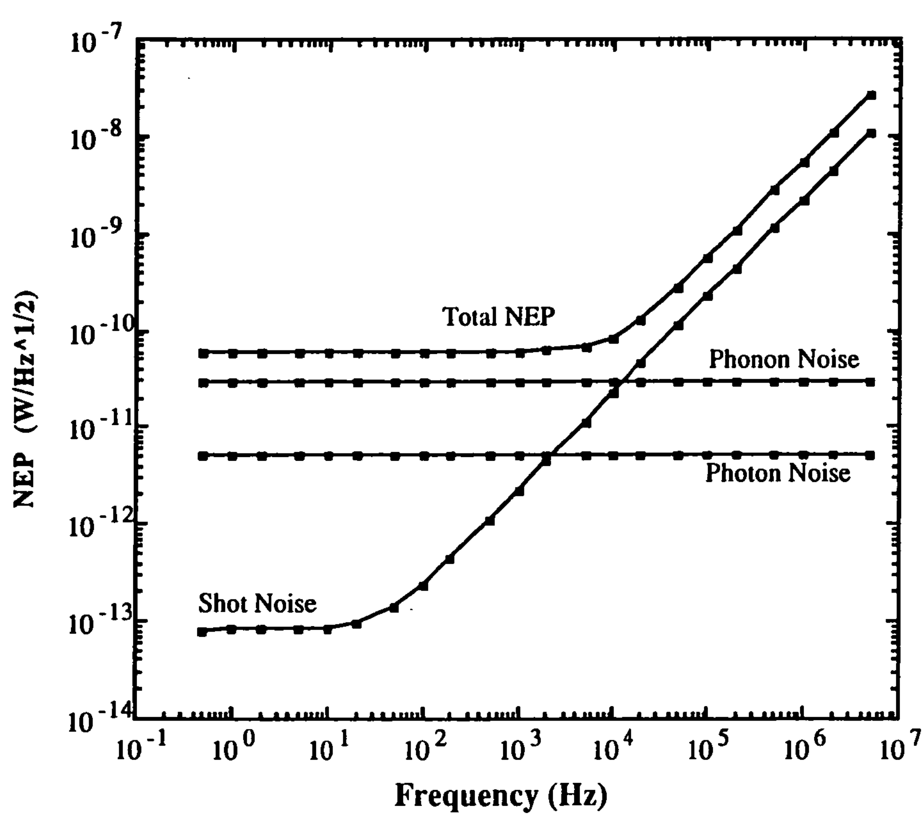
Area	$A = 10^{-2}$	cm^2
Thermal conductance between membrane and surroundings : Dominated by air in cavity	$G = 2 \times 10^{-4}$	W/K
Heat capacity of membrane and gas : Dominated by membrane	$C = 8 \times 10^{-7}$	J/K
Time constant (C/G) :	$\tau = 4 \times 10^{-3}$	s
Response coefficient of thermo-electric transducer : $\alpha = \frac{1}{I}\frac{\partial I}{\partial z}\frac{\partial z}{\partial T}$	$\alpha = 2.3 \times 10^{4}$	/K
Detector responsivity : $S = \frac{I\,\alpha}{(G^2 + (\omega C)^2)^{1/2}}$	$S = 0.38$	A/W

Fundamental Noise in the Tunnel IR Detector

$$(NEP)^2 = \underset{\text{phonon}}{4k_BT^2G} + \underset{\text{photon}}{16A\sigma k_BT^5} + \underset{\text{electron}}{\frac{2eI(G^2+(\omega C)^2)}{I^2\alpha^2}} + \underset{\text{amplifier}}{\frac{I_n^2(G^2+(\omega C)^2)}{\omega I^2\alpha^2}}$$

- Since α is very large in this detector, the electron and amplifier noise terms are only important for frequencies $\omega >> 1/\tau$.
- At low frequencies, the phonon noise dominates. Improvements can only be obtained through reductions in G
- The prototype Tunnel IR Detector is expected to have NEP of 6×10^{-11} W/$\sqrt{\text{Hz}}$ at frequencies below 10 kHz.

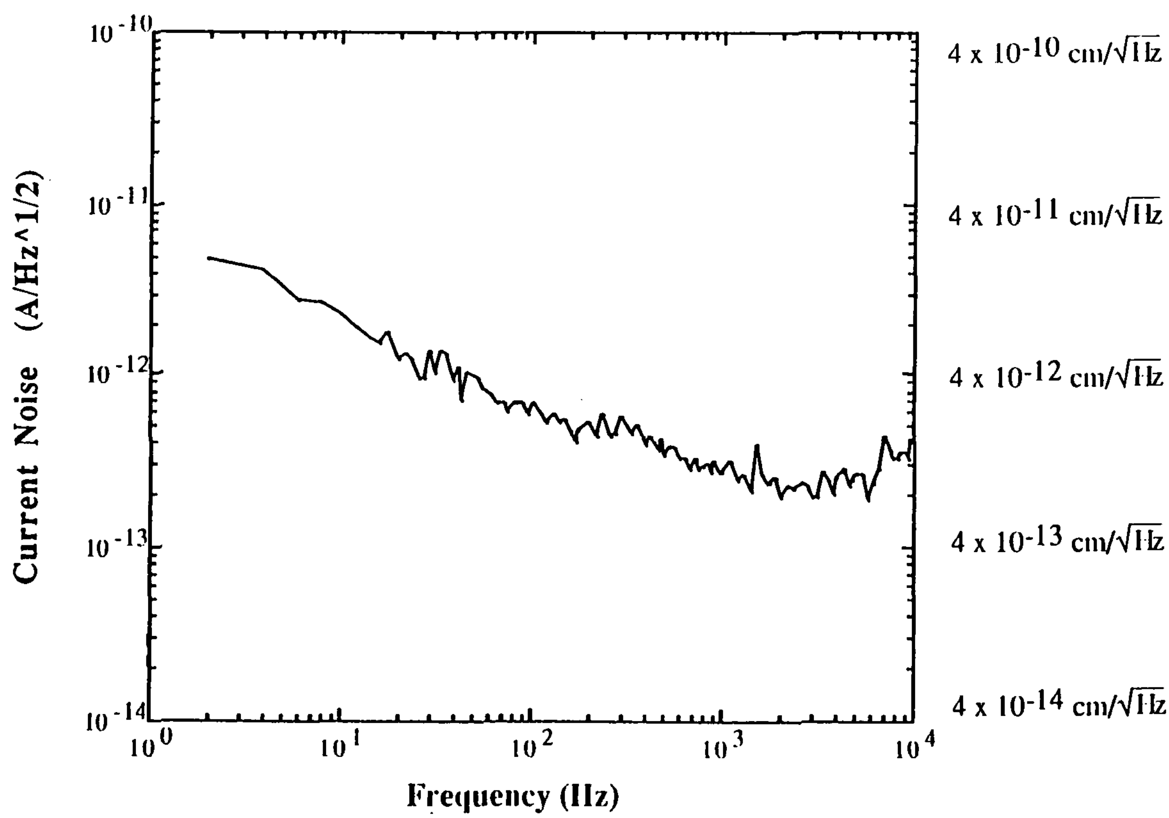
Calculated Contributions to the NEP



Sensor Construction : Present Status

Micromachined Springs	Fabricated
Micromachined Tips	Fabricated
Free-Standing Silicon Oxy-Nitride Membrane	Fabricated
Metallization	Complete
Transducer Characterization	Almost Complete
Infrared Sensor Assembly	Next
Sensor Characterization	

Measured Current Noise



Speculations

The NEP of the Tunneling IR Detector can be improved by reducing the thermal conductance to the heat sink as follows:

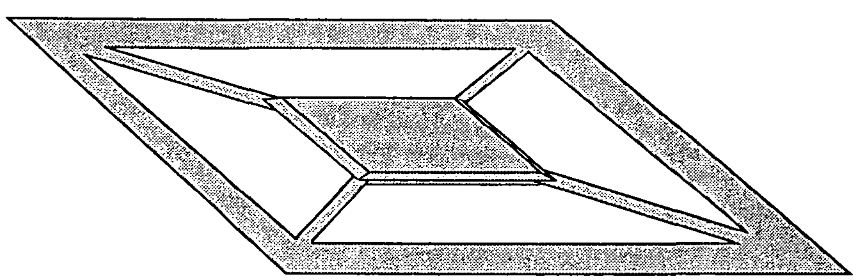
- Replace the air in the cavity with Xenon.
- Increase thickness of cavity to 400 μm
- Reduce the cavity area to 500 μm x 500 μm.

Combined effect is to reduce NEP by a factor of approximately 6.

Further reductions in the NEP of the prototype IR Tunnel Sensor are constrained by the thermal contact to the walls of the cavity, which act as a heat sink.

By vacuum-encapsulating a 'bag' of gas, the thermal conductance may be reduced much further. Improvements in the NEP of more than an order of magnitude are likely.

Vacuum-Encapsulated IR Sensor



- Air-filled silicon oxy-nitride balloon supported by silicon oxy-nitride ribbons.
- Au film on balloon for IR absorption and tunneling electrode.
- Active area = 50 mm x 50 mm.
- Thermal conductance to heat sink limited by ribbons : G = 16 nW/K
- Predicted NEP is limited by background fluctuations (BLIP Limit)

Conclusions

- We have designed a device based on the Pneumatic Infrared detector, but which is constructed entirely from micromachined silicon and uses a vacuum tunnel sensor to detect the expansion of the trapped gas.
- A calculation of the performance of this device, which is based only on thermal physics and the known characteristics of tunneling has been carried out.
- The performance of the prototype is expected to meet or exceed that of all room temperature detectors which operate in the LWIR.
- Fabrication and characterization of the components of the detector is under way.
- Simple modifications to the design of the prototype can improve its NEP by a factor of 6. More complicated modifications can lead to more substantial improvements in the NEP.