Integration and Packaging Concepts for Infrared Bolometer Arrays

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Abstract

Infrared (IR) imaging devices based on energy detection has shown a dramatic development in technology along with an impressive price reduction in recent years. However, for a low-end market as in automotive applications, the present cost of IR cameras is still the main obstacle to broadening their usage. Ongoing research has continuously reduced the system cost. Apart from decreasing the cost of infrared optics, there are other key issues to achieve acceptable system costs, including wafer-level vacuum packaging of the detectors, low vacuum level operation, and the use of standard materials in the detector fabrication. This thesis presents concepts for cost reduction of low-end IR cameras.

The thesis presents a study of detector performance based on the thermal conductance design of the pixel. A circuit analog is introduced to analyze the basic thermal network effect from the surrounding environment on the conductance from the pixel to the environment. A 3D simulation model of the detector array conductance has been created in order to optimize the performance of the arrays while operated in low vacuum. In the model, Fourier’s law of heat transfer is applied to determine the thermal conductance of a composite material pixel. The resulting thermal conductance is then used to predict the performance of the detector array in low vacuum.

The investigations of resist as the intermediate bonding material for 3D array integration are also reported in the thesis. A study has been made of the nano-imprint resists series mr-I 9000 using a standard adhesive wafer bonding scheme for thermosetting adhesives. Experiments have been performed to optimize the thickness control and uniformity of the nano-imprint resist layer. The evaluation, including assessment of the bonding surface uniformity and planarizing ability of topographical surfaces, is used to demonstrate the suitability of this resist as sacrificial material for heterogeneous detector array integration.

Moreover, the thesis presents research in wafer-level packaging performed by room temperature bonding. Sealing rings, used to create a cavity, are manufactured by electroplating. The cavity sealing is tested by liquid injection and by monitoring the deflection of the lid membrane of the cavities. A value for the membrane deflection is calculated to estimate the pressure inside the cavities.
## Contents

### Abstract

### List of papers

1. **Introduction**  
   1.1 General introduction .......................................................... 1  
   1.2 Objectives ................................................................................. 2  
   1.3 Structure .................................................................................. 2

2. **Infrared imaging**  
   2.1 Thermal radiation and atmospheric effect ......................... 3  
   2.2 Infrared imaging system .......................................................... 4  
      2.2.1 Detector unit technology ................................................... 6  
      2.2.2 System noise ................................................................... 10  
   2.3 Infrared imaging for commercial applications ................. 12

3. **Thermal imaging detector**  
   3.1 Radiant energy transfer .......................................................... 15  
   3.2 Uncooled bolometer thermal detection .................................. 16  
      3.2.1 Bolometer physics and figures of merit ................................ 17  
   3.3 Heat transfer mechanism ........................................................ 19  
   3.4 Bolometer array operated in atmospheric environment ........ 21  
      3.4.1 Thermal conductance modeling of microbolometer arrays .... 23  
      3.4.2 Simulation result and array performance effect ............. 26  
   3.5 Discussion ............................................................................... 28

4. **3D integration for infrared bolometer arrays** ................. 29  
   4.1 Introduction ............................................................................ 29  
   4.1.1 Transfer bonding for bolometer FPAs .............................. 30  
   4.2 Polymers as bonding intermediate in 3D integration ............ 31  
      4.2.1 Nano-imprint resist in 3D integration of bolometer .......... 32  
      4.2.2 Experiments and evaluation of material ...................... 32
5. Room temperature packaging
   5.1 Introduction to MEMS packaging ................................................. 37
   5.2 Wafer-level packaging ............................................................... 37
   5.3 Room temperature micro-cavity sealing for bolometer arrays .......... 40
      5.3.1 Cold welding conceptual packaging ...................................... 40
      5.3.2 Sealing rings ................................................................. 42
      5.3.3 Experiments and evaluation of cavity sealing ...................... 43

6. Summaries of the appended papers .............................................. 47

7. Conclusions ................................................................................ 49

Acknowledgement ......................................................................... 51

References .................................................................................. 53

Paper reprints ............................................................................ 59
List of Papers

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3. Part of design and experiments and part of writing
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1 Introduction

1.1 General introduction

To enhance the capability of seeing in difficult light conditions, substantial efforts are being made. One of the approaches is infrared (IR) thermal imaging where the electromagnetic radiation emitted by the objects is used to form an image. The infrared radiation covers spectral region ranges in wavelength from $0.75 \mu m$ to $1000 \mu m$. The applications and technologies described in this thesis focus on the band of the wavelength beyond $1.4 \mu m$.

In principle, the IR detection mechanisms are divided into two groups; photon detection and energy detection. In the early days of IR imaging, only photon detectors were available while the energy detectors could not meet the performance criteria. Due to the relatively high price, high energy consumption and bulky size of the photon detectors, IR imaging usage was limited mostly to military applications. Despite the drawbacks, nowadays photon detectors are still used in some applications where the device performance is the main issue, such as in weapon platforms, in space observation instruments or in special medical instruments, with prices on the order of $50,000–150,000$.

Energy detectors, demand a fabrication technology for implementing the micro-scale pixels. During the last few decades, MEMS technology has emerged. This opens up for micro-scale detector manufacturing. This leads to a striking performance improvement of the detector, making it applicable for camera usage, leading to a new generation of low-cost IR cameras. Infrared cameras, with MEMS detectors based on energy detection, are small in size, consume less power and are much less expensive (typically $8000–15000$), opening for various civilian applications like security cameras, heat analysis and driver's night vision enhancement. However, for commercial applications as in automotive night vision systems, the cost is the main issue. To enable high-volume applications, the cost should be as low as possible. Although energy detection technology is now already much cheaper than photon detector technology, the costs are still high and remain a barrier for their growth in cost-sensitive mass markets. Thus, there are continuing efforts to decrease the cost of cameras to much lower values of $50–500$.

In IR imaging systems, the detector unit is one of the most important and most expensive part. Thus, to make a cost efficient camera, the effort should focus on reduction of the detector unit cost. The research challenge is to reduce the system cost while achieving reasonable performance for a specific application. The following are the issues that should be considered in the research for a cost efficient camera implementation:
(1) simple structure and fabrication process
(2) no exotic materials
(3) low-cost vacuum sealing and lens technology

1.2 Objectives

This thesis describes research in the field of microsystem technology particularly, design and manufacturing techniques for cost efficient commercial IR camera detector chips. The objective of this study is to demonstrate three concepts for cost reduction of the IR detector chip. The study includes investigations of heterogeneous 3D integration, room-temperature vacuum packaging and the use of standard semiconductor materials for the bolometer fabrication.

1.3 Structure

This thesis consists of the following chapters;

Chapter 2 provides a brief overview of IR radiation and IR imaging systems for terrestrial object detection.

An overview of the heat energy transfer relevant to resistive bolometer physic and its parameters is given in chapter 3. The circuit model and simulations of the thermal conductance of bolometer detector arrays are discussed.

Chapter 4 provides an overview of heterogeneous 3D integration for bolometer detector arrays and the requirement on the fabrication. The resulting evaluations, including bonding surface uniformity and surface topography completing ability are reported herein.

Chapter 5 introduces background of MEMS packaging along with wafer-level packaging. A packaging concept based on cold welding is introduced. The evaluation of sealed cavities are presented and discussed.
2 Infrared Imaging

This chapter is a brief description of the terms most commonly encountered with terrestrial infrared imaging systems.

2.1. Thermal radiation and atmospheric effect

All objects in the universe which have temperatures above absolute zero radiate electromagnetic energy. A blackbody is an object that is a perfect emitter of thermal electromagnetic radiation. The distribution of the thermal radiation of a blackbody as a function of the wavelength follows the Plank law:

\[ M(\lambda, T) = \frac{2hc^2}{\lambda^5 \left[ \exp \left( \frac{hc}{\lambda kT} \right) - 1 \right]} \]  \hspace{1cm} (2.1)

where \( M(\lambda, T) \) is the spectral radiant exitance in watt per square meter of area and micrometer of radiation wavelength (W/m²μm), \( \lambda \) is the emitted wavelength in micrometers (μm), \( T \) is the absolute temperature of the blackbody in Kelvin (K), \( h \) is Planck's constant \( (6.626176 \times 10^{-34} \text{ W} \cdot \text{s}) \), \( c \) is the speed of light \( (2.998 \times 10^8 \text{ m/s}) \), \( k \) Boltzmann's constant \( (1.380662 \times 10^{-23} \text{ W} \cdot \text{s/K}) \). Figure 2.1 shows a plot of the curves for a number of black body temperatures. Wien’s displacement law give a relation between temperature and the wavelength peak of the Eq. (2.1). The values of the wavelength of maximum radiation \( \lambda_{\text{max}} \) per unit

![Figure 2.1 Curve of emission of black body corresponding to wavelength range 1-100μm [1].](image-url)
area are shown as the intersection point of the dash-dot line and black-body temperature curves in figure 2.1. The relation between $\lambda_{\text{max}}$ and black-body temperature is given by

$$\lambda_{\text{max}}T = 2898 \ \mu\text{mK} \quad (2.2)$$

Infrared (IR) is electromagnetic radiation with wavelengths in the range of 0.7$\mu$m –1mm (wavelengths longer than those of visible light, but shorter than those of radio waves). In terms of specific applications, the IR spectrum can be divided in more ranges as shown in table 2.1.

The atmosphere can also have an effect on the IR spectral range. As IR radiation propagates through a medium, the amount of radiation reaching the receiver is depending on atmosphere attenuation characteristics, which acts as a spectral pass band filter. The dominant atmospheric attenuation is caused by constituent gases in the atmosphere, mainly nitrogen, oxygen, carbon dioxide, water vapor, ozone and methane. The IR spectral transmission bands propagating through atmosphere are shown in figure 2.2.

### Table 2.1 IR spectral band [2].

<table>
<thead>
<tr>
<th>Name</th>
<th>Wavelength range ($\mu$m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Near infrared (NIR)</td>
<td>0.78-1</td>
</tr>
<tr>
<td>Short-wave infrared (SWIR)</td>
<td>1-3</td>
</tr>
<tr>
<td>Mid-wave infrared (MWIR)</td>
<td>3-6</td>
</tr>
<tr>
<td>Long-wave infrared (LWIR)</td>
<td>6-15</td>
</tr>
<tr>
<td>Very long-wave infrared (VLWIR)</td>
<td>15-1000</td>
</tr>
</tbody>
</table>

![Figure 2.2 Atmosphere absorption of the IR spectral band (adapted from [3]).](image)

2.2. Infrared imaging systems

The detection principle difference between regular visible light detection and energy detection schemes is that visible light detectors dominantly detect ray of light source that is incident and is then reflect from the object. In case the object temperature is high (>1000 K), the object radiates the visible light energy then the detector is able to detect the radiated ray from the object directly. An object that has a temperature above 0 K does radiate energy. In energy detection, the detectors directly detect radiation from the objects as depicted in figure 2.3 b. However, the energy detector can be interfered by reflected radiation from other
sources (e.g. sunlight). As shown in table 2.1, there are several ranges of the IR spectral band. The different bands are useable in different applications. In general, the operating spectral band selection is based on a wavelength region where a strong image signature exists and also based on interfering background and atmospheric radiation and absorption effects.

From Wien's displacement law (Eq. 2.2) it can be seen that objects at near room temperature (300 K) emit infrared rays peaked at around 10 μm. Considering black body emission curves together with atmospheric window transmittance, the LWIR band is most useable for terrestrial object detection applications. It has optimal properties of atmospheric transmittance and wavelength energy emitting. Furthermore, the LWIR is more sensitive to ambient-temperature objects and transmits through mist and smoke. Ground-level solar radiation effects can be disregarded in LWIR [4, 5]. For hotter objects, or if contrast is more important than sensitivity, MWIR may be more suitable [4]. Figure 2.4 shows the comparison of images taken from a normal camera and an infrared camera in a smoky environment.

**Figure 2.3** Concept of regular visible light (a) and infrared detection (b).

**Figure 2.4** Comparison of image by regular camera (a) and by IR camera (b) [6].

The block diagram of an infrared system shown in figure 2.5 illustrates that radiation of emitted energy from an object propagates through the atmosphere and reaches the infrared sensor through its optical system. The detector then converts
the infrared energy to a video signal, whose amplitudes are proportional to the intensity in the scene. The signal is made visible to the eye by a display unit.

![Schematic picture of thermal imaging system](adapted from [17]).

### 2.2.1 Detector unit technology

**Ray processing**

There are two different principle types of ray processing systems. Scanning systems measure surface radiation point by point. The object points are transferred to a single infrared detector by oscillating mirrors and rotating prisms. The scanning can be done either by moving the sensor as a whole or by moving internal and/or external scan mirrors. Staring systems use infrared sensor arrays (focal plane arrays). Every element of the object is imaged on a corresponding sensor element of the focal pane. For applications with weight and size limitation, the staring sensor usually provides a smaller system for the same sensitivity. A staring system ideally can use all the radiation that passes its lens aperture, while the scanning system only uses the energy in on pixel at a line. Since the sensors look at one whole scene at one time, any target in the scene can be recognized in a

![Operation principle of a) IR focal plane arrays b) mechanically scanned IR imager](Courtesy of Hughes Missile Systems Division).
real time sequence. Starers are usually composed of two dimensional mosaic focal plane arrays. Schematics of staring and scanning sensors are shown in figure 2.6 [7].

**Detection mechanisms**

Infrared detectors are typically divided into two fundamental groups; photon detectors and thermal (energy) detectors.

**Photon detectors**

The photon detectors are classified into different types such as intrinsic, extrinsic, quantum well [1, 8, 9] and photoemissive devices (the effect involves the emission of electrons from a surface, when light of wavelength shorter than the cutoff wavelength falls on the surface) [1]. In photon detection, detectors generate free charge carrier when the light quanta impinge on the detection area resulting in an output current or a voltage across the detector. Photon detectors have a wavelength-dependent spectral response [10], since they respond only when [11]

\[ E < \frac{h}{\lambda} \quad (2.3) \]

where \( E \) is the energy gap, \( h \) is the Plank constant and \( \lambda \) is the cutoff wavelength. The detectors are fabricated and based on semiconductor materials with narrow band gaps or metal-semiconductor structures (Schottky barriers), which are only operated efficiently when

\[ k_B T < \frac{h}{\lambda} \quad (2.4) \]

where \( k_B \) is the Boltzmann constant, \( T \) is the detector temperature, and \( \lambda \) is the detected wavelength. This detector type exhibits both perfect signal to noise performance and a very fast response. However, to obtain such performances, they require cooling to suppress thermal generation of charge carries and thermal noise that varies as \( \exp[-\frac{e_s}{k_B T}] \) [11]. The effect increases proportionally to the wavelength beyond the near infrared, meaning that longer wavelengths require lower operating temperatures. For instance, most LWIR detectors operate at about 77K, MWIR operate at about 200K which can be cooled by liquid nitrogen and thermo electric coolers (TEC) respectively [5]. There are many materials in use for photon detection such as Pbs, InSb, HgCdTe and SiGa. Figure 2.7 shows detector materials used for operating in different wavelength ranges and their operating temperatures [7]. Since photo-detectors require cooling systems to maintain the perfect performance, they are costly, bulky, power consuming and have a finite lifetime.
Thermal detectors

The thermal detectors are classified according to their operating scheme: thermopile, bolometer, thermomechanical or pyroelectric. Most thermal detectors operate at room temperature with moderately varying performance with temperature, and have a broad region of spectral response [10]. These so-called uncooled detectors do not require detector cooling.

A thermal detector can simply be modeled as shown in figure 2.8. The detector element is suspended by two low-thermal conductance wires, which are connected to the heat sink. When a radiation input is received by the detector, the temperature change is found by solving the heat balance equation (neglecting the radiation heat loss)

$$C_{th} \frac{d\Delta T}{dt} + G_{th} \Delta T = \varepsilon \Phi$$

where $C_{th}$ is the thermal capacitance, $G_{th}$ is the thermal conductance, $\Delta T$ is the temperature difference due to the optical signal $\Phi$ between the detector and its surroundings, and $\varepsilon$ is the emissivity of the detector.

The detector materials are heated by the incoming IR radiation that in turn changes a physical or electrical property of the temperature-dependent detectors. Since a change in temperature takes place, the thermal detectors are naturally slow in response. The amount of a detect or temperature change is influenced by the thermal capacity or thermal mass. In order to have a small thermal capacity, the absorber is typically made in small volume which yields a shorter response time. By implementing a detector in micro-scale, the response time is reduced to tens of milliseconds. This is fast enough for the normal TV frame rates at 25-30 Hz operation.
Focal plane arrays

Focal plane arrays (FPAs) are detectors which consist of linear or two dimensional matrixes of individual elements located at the focus of the imaging system. In advanced IR imaging systems, infrared FPAs are a key component, whose technology has the potential to dramatically reduce IR system complexity and cost resulting in the use of smaller optical apertures, reduced spectral bandwidths and faster frame rates. The use of 2D arrays is especially advantageous in staring mode. The main advantage is due to the avoidance of all mechanical scanning.

Due to much longer integration times, the sensitivity is increased. The FPA area consists of row and columns of pixels. The detectors are contiguous as depicted in figure 2.9. In the example in figure 2.9b the detector does not completely fill the cell area. The ratio of active detector element area \( A_{\text{Detector}} \) to the cell area \( A_{\text{Cell}} \) is the fill factor \( \beta \), or \( \beta = \frac{A_{\text{Detector}}}{A_{\text{Cell}}} \). In the example in figure 2.9a the detector area entirely fills the cell area, and thus \( \beta = 1 \). The fill factor \( \beta \neq 1 \) has an effect on the FPA performance [13, 14].

Hybrid and monolithic FPAs

A number of architectures are used for IR FPAs. In general, they may be classified as hybrid and monolithic.

The hybrid FPAs consists of two components; detector array (figure 2.10a) and a Readout Integrated Circuit (ROIC) multiplexer (figure 2.10b,c), detectors and multiplexers are fabricated on separated substrates and interconnected with each other by bump bonding which provides mechanical support and electrical conduction. They are joined by means of flip-chip bonding or loophole interconnection. The fill factors of the hybrid FPAs are near 100%. Furthermore their detector material and the ROIC multiplexer can be optimized independently.

Monolithic FPAs are fabricated based on direct integration of the detector array onto silicon ICs. Some of the signal multiplexing may be done in the detector material itself and some in an external readout circuit. Monolithic FPAs offer important advantages of minimum focal plane interconnection size. The figure 2.10 d,e show monolithic detector and its multiplexer.

2.2.2 System noise

Noise is defined as any unwanted signal component. All system parts can exhibit noise which cause degrading of the total system performance in terms of the signal to noise ratio. The frequency distribution of noise is characterized by a power spectrum. From figure 2.5, the detector system noise can be subdivided in three major classes [17].
**Photon Noise**
- Noise due to the signal radiation
- Noise due to the background radiation

**Detector-Generated Noise**
- Johnson Noise
- 1/f Noise
- Temperature fluctuations

**Post-detector Electronic Noise**
- Read out Circuit Noise

The photon noise is the uncertainty in the amount of electromagnetic radiation emitted by any signal source including the background within a fixed period of time. The Johnson noise is caused by the random thermal motion of charged particles in a resistive element. The 1/f noise is due to lack of electric contact and also due to electrically active surfaces or bulk material phenomena. The temperature fluctuation noise is the unwanted output signal from any temperature fluctuations of the detector element that are not due to the change in the input signal. There are several noise processes introduced by the readout electronics. Post detector electronics exhibit the entire noise source also listed in detector-generated noise.

For imaging thermal IR detector systems, the noise equivalent temperature difference (NETD) is an important parameter used for characterizing the signal performance. The NETD is applicable to IR detector focal plane arrays and is defined as the difference in temperature between two side-by-side blackbodies which corresponds to a difference in signal-to-noise ratio of 1 in the electrical outputs [18-23]. The capability of an IR imager to distinguish slight temperature of emissivity differences of objects, is indicated by small values of NETD. The NETD is proportional to the total noise voltage $V_N$ of the detector, and $V_N$ relates to detector-generated noise and post-detector electronic noise components with [23]

$$V_N^2 = \frac{V_{1/f}^2}{7} + V_{\text{johnson}}^2 + V_{\text{thermal}}^2 + V_{\text{ROIC}}^2$$

(2.6)

where $V_{1/f}$ is the 1/f-noise voltage, $V_{\text{johnson}}$ is the Johnson noise voltage, $V_{\text{thermal}}$ is the thermal fluctuation noise voltage and $V_{\text{ROIC}}$ is the total read-out integrated circuit noise voltage. The NETD model calculation analysis is described in detail in paper I.
2.3. Infrared imaging for commercial applications

IR thermal imaging has been used in many application areas, some of which are shown in table 2.2. However, in terms of technology development, infrared imaging applications can be divided into two principal categories: military applications (high-end technology where performance is the main issue) and civilian applications (low-end technology where the cost is the main issue). By utilizing low cost technology, the civilian systems have spun off from the military systems.

To produce a cost efficient camera, its detector array is designed to be small feature. There are several potential benefits of reducing the pixel size [24], one of which is cost reduction of the infrared optics. Since the IR lenses usually are fabricated from expensive materials such as zinc selenide (ZnSe) or germanium (Ge), decreasing the optic size result in reducing the cost of camera. The pixel pitch is related to the system parameters such as the ratio of the effective focal length to the aperture diameter \(D_o\) (F-number) and the operation wavelength [25]. Given that the F-number is constant, a smaller aperture diameter requires a smaller pixel. In addition, a reduction of aperture diameter would reduce overall size and weight of the system. However to make a small pixel it would be difficult to achieve a high fill-factor with available technology. Thus the development of a low-cost IR detector relies on micromachining process technology improvement.

For most low-end applications, the performance of the IR system is not the primary issue. The energy detector technology seem to be utmost suitable for such systems and one type of energy detectors, monolithically uncooled bolometers integrated on ROIC in form of staring focal plane arrays, shows an attractive trade-off between system cost and performance. Table 2.3 shows a comparison of different detector types.
<table>
<thead>
<tr>
<th>Military, Law Enforcement And Rescue</th>
<th>Industrial</th>
<th>Medical</th>
<th>Scientific</th>
</tr>
</thead>
<tbody>
<tr>
<td>Night operations</td>
<td>Industrial surveillance and crime prevention</td>
<td>Early detection and identification of cancer</td>
<td>Satellite earth resource</td>
</tr>
<tr>
<td>Reconnaissance and surveillance</td>
<td>Process control</td>
<td>Optimum site for amputation determination</td>
<td>Surveying</td>
</tr>
<tr>
<td>Fire fighting and rescue in smoke</td>
<td>Nondestructive inspection of manufactured items such as thermal insulators, photographic film and infrared materials</td>
<td>Placement site location</td>
<td>Gulf Stream location and mapping</td>
</tr>
<tr>
<td>Submarine detection</td>
<td>Hidden piping location</td>
<td>Efficiency of arctic clothing studies</td>
<td>Volcano studies</td>
</tr>
<tr>
<td>Detect underground missile sites, personnel, vehicles, weapons, mines and encampments</td>
<td>Microwave fields display</td>
<td>Early diagnosis of incipient stroke and vein blockage</td>
<td>Water pollution detection and studies</td>
</tr>
<tr>
<td>Damage assessment</td>
<td>Diseased Tree and crop detection</td>
<td>Wound healing monitoring</td>
<td>Crevasse and sea-ice</td>
</tr>
<tr>
<td>Night-time landing aids</td>
<td>Hot spot detection, e.g., hot boxes on railroad cars and power lines</td>
<td>Onset of infection detection without removing bandages</td>
<td>Reconnaissance studies</td>
</tr>
<tr>
<td>Missile guidance and proximity fusing</td>
<td>Brake linings, cutting tool, weld, and ingot temperature measurement</td>
<td></td>
<td>Crop detection</td>
</tr>
<tr>
<td>Earthquake victim locations</td>
<td>Clear-air turbulence detection</td>
<td></td>
<td>Forgery detection</td>
</tr>
<tr>
<td>Hidden law violator location</td>
<td>Organic chemicals and gas analysis</td>
<td></td>
<td>Nocturnal animal studies</td>
</tr>
<tr>
<td>Fire detection</td>
<td>Pipeline leak detection</td>
<td></td>
<td>Remote sensing of weather conditions</td>
</tr>
<tr>
<td></td>
<td>Oil spill detection</td>
<td></td>
<td>Heat transfer in plant studies</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Earth’s heat balance measurements</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Farming techniques improvement</td>
</tr>
</tbody>
</table>
Table 2.3. Comparison of IR imagers [10].

<table>
<thead>
<tr>
<th>Feature</th>
<th>Present scanned Cryogenic imagers</th>
<th>Cryogenic staring imagers</th>
<th>Uncooled microbolometer imagers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Approximat system cost</td>
<td>$100,000 (military volume production)</td>
<td>$100,000 (military volume production)</td>
<td>$1000 (high-volume production)</td>
</tr>
<tr>
<td>Typical focal plane temperature</td>
<td>100 K</td>
<td>100 K</td>
<td>Room temperature</td>
</tr>
<tr>
<td>IR sensor</td>
<td>HgCdTe, InSb</td>
<td>HgCdTe, InSb, PtSi, GaAs/AlGaAs</td>
<td>Micromachined Si and VOx</td>
</tr>
<tr>
<td>Typical NETD</td>
<td>0.1°C</td>
<td>0.01°C</td>
<td>&gt; 0.05°C</td>
</tr>
<tr>
<td>Application</td>
<td>Military and specialized industrial applications</td>
<td>Military and specialized industrial applications</td>
<td>Widespread applications for military, commerce, research, industrial applications</td>
</tr>
</tbody>
</table>
3 Thermal Imaging Detector

3.1 Radiant energy transfer

To characterize the power transferred from the source to the detector, the geometry of the source-detector system need to be known. Let us assume that the radiant surface, the receiving aperture, and the receiving detector are collimated. For the source that the plane source normal to the line of sight to a plane detector, which is also normal to the optical axis, the relation between the spectral flux $\Phi_\lambda$ on the optical collecting aperture and the radiance $L_\lambda$ from the source is then

$$\Phi_\lambda = L_\lambda \tau_a(\lambda) \frac{A_s A_o}{R^2}$$

(3.1)

where $A_s$ is the source area, $A_o$ is the receiving aperture area locating at the range $R$ from the sources, $\tau_a(\lambda)$ is the atmospheric transmittance between the source and the infrared system and $L_\lambda$ is the power transferred per unit emitter area and unit receiver projected solid angle.

The source signature is described by its radiant exitance $M$ which is defined previously by Eq.(2.1). Given the source is Lambertian radiator that the radiance $L_\lambda$ equals $M_\lambda/\pi$ [17]. For the case of the extended surfaces as illustrated in figure 3.1, the source dimensions are much larger than the detector. The detector is assumed to be rectangular with linear dimensions $a$ and $b$ and the object-to-sensor distance $R$ much greater than aperture diameter. For sufficient large $R$, small-angle approximations may be made to simplify the equation [18]. The detector

![Figure 3.1 Optical energy collection (adapted from [18]).](image-url)
collects radiance from a source area of $\alpha \beta R^2$ corresponding to the area projection of the detector solid angular at the range $R$. Thus Eq.(3.1) can be rewritten as

$$\Phi_{\lambda o} = \alpha \beta R^2 L_{a} \tau_a(\lambda) \frac{A_o}{R^2}$$  \hspace{1cm} (3.2)

The detector is separated from the optical system by the focal length $f$. The spectral flux of the radiation reaching the detector element is

$$\Phi_{\lambda d} = \tau_o(\lambda) \Phi_{\lambda o}$$  \hspace{1cm} (3.3)

where $\tau_o(\lambda)$ is the transmission of the optics. Substitute (3.2) in (3.3) and rearrange the equation then

$$\Phi_{\lambda d} = \tau_o(\lambda) \alpha \beta L_{a} \tau_a(\lambda) A_o$$  \hspace{1cm} (3.4)

The F-number $(f/\#)$ is defined as the ratio of the effective focal length $f$ to the aperture diameter $D_o$. The projected detector solid angle in radians is $\omega A$ which equals the product $\alpha \beta$. For circular optical aperture then

$$\alpha \beta A_o = \frac{ab \pi D_o^2}{f^2} = \frac{\pi A_d}{4(f/\#)^2}$$  \hspace{1cm} (3.5)

replace $\alpha \beta A_o$ in (3.4) by (3.5) yielding the expression for the spectral flux or power on the detector in term of detector system parameters relation,

$$\Phi_{\lambda d} = \frac{\pi A_d}{4(f/\#)^2} L_{a} \tau_o(\lambda) \tau_a(\lambda)$$  \hspace{1cm} (3.6)

For the exact expression the factor $[4(f/\#)]^2$ can be replaced by the factor $[1 + 4(f/\#)]^2$ [18].

3.2 **Uncooled bolometer thermal detection.**

Resistive bolometers are thermal detector whose electrical resistance $R_b$ changes with the absorbed IR irradiance. The relation between a temperature change $\Delta T$ and a resistance change $\Delta R_b$ is
\[ \Delta R_b = \alpha R_b \Delta T \quad (3.7) \]

where \( \alpha \) is a temperature coefficient of resistance (TCR) and is defined as

\[ \alpha = \frac{1}{R_b} \frac{dR_b}{dT} \quad (3.8) \]

### 3.2.1 Bolometer physics and figures of merit

This section introduces some useful parameters describing thermal detector performance. Regarding the detector pixel, when its sensitive area is heated up by incidental IR radiation, its physical or electrical material property is changed. A simple analysis of the detector thermal parameters can be derived from Eq. (2.5) in chapter 2. Assuming the radiant power in this equation to be a periodic function with angular frequency \( \omega \)

\[ \Phi = \Phi_0 e^{i\omega t} \quad (3.9) \]

where \( \Phi_0 \) is the amplitude of sinusoidal radiation, then the solution of the differential equation is given by [27]

\[ \Delta T = \frac{\varepsilon \Phi_0 e^{i\omega t}}{G_{th} + i\omega C_{th}} = \frac{\varepsilon \Phi_0}{G_{th} \sqrt{1 + \omega^2 \tau_{th}^2}} \quad (3.10) \]

To achieve a high \( \Delta T \), the thermal conductance \( G_{th} \) of the link between the detector and the heat sink should be as small as possible. In Eq. (3.10), the thermal time constant is defined as

\[ \tau_{th} = \frac{C_{th}}{G_{th}} = C_{th} R_{th} \quad (3.11) \]

The thermal capacity relates to the volume of the detector \( V \), the density \( \rho \) and specific heat \( c \) as \( C_{th} = V \rho c \). From the above equation, the time constant determines the speed of response of thermal detectors. If the detector has a large \( C_{th} \) value, its temporal response will be slow. The frequency response of a detector temperature change (Eq. 3.10) is shown in figure 3.2. At the 3 dB point, the frequency that relates to \( \tau_{th} \) is

\[ f_c = \frac{1}{2\pi\tau_{th}}. \]
Now consider the electrical parameter of a detector. The signal voltage change across the bolometer element is

$$\Delta V_s = I(\Delta R_b) = I(\alpha R_b \Delta T) \quad (3.12)$$

where $I$ is the current pass through the bolometer. Using $\Delta T$ from Eq. (3.10) substitute in (3.12) yield

$$\Delta V_s = \frac{\alpha R_b \varepsilon \Phi_0 I}{G_{th} \sqrt{1 + \omega^2 \tau_{th}^2}} \quad (3.13)$$

The responsivity $\mathcal{R}$ is determined by the ratio of the detector signal (detector output) to the optical power incident on the detector (detector input), $\mathcal{R} = \Delta V_s / \Phi_0$. Thus,

$$\mathcal{R} = \frac{\alpha R_b \varepsilon I}{G_{th} \sqrt{1 + \omega^2 \tau_{th}^2}} \quad (3.14)$$

The minimum detectable radiant flux of the detector is known as the noise equivalent power NEP and is defined as the noise level $V_N$ divided by the responsivity $\mathcal{R}$. The incident flux required to give an output signal voltage equal to the noise voltage, i.e. to give a signal-to-noise ratio of unity. Thus

$$\text{NEP} = \frac{V_N}{\mathcal{R}} \quad (3.15)$$

The figure of merit usually used for the detectors is the reciprocal of NEP, the detectivity $D$:

$$D = \frac{1}{\text{NEP}} \quad (3.16)$$
3.3 Heat transfer mechanism

Heat transfer is energy in transit due to a temperature difference. There are three modes of heat transfer:

1. Conduction
2. Convection
3. Radiation

For microbolometer detectors in a hermetic vacuum package, the radiation and convection are so small that they can be neglected [28, 29].

**Heat Conduction and thermal conductance**

When a temperature gradient exists within a body, heat energy will flow through an element of material from the region of high temperature to the region of low temperature. This phenomenon is known as conduction heat transfer describing by Fourier’s Law [30, 31].

\[
\mathbf{q} = -\lambda_T \nabla T
\]  

(3.17)

The heat flux vector \( \mathbf{q} \) (W/m²) is the quantity of heat transferred per unit time across a unit area and is proportional to the local temperature gradient \( \nabla T \). The thermal conductivity \( \lambda_T \) (W/Km) is a thermophysical material property. The minus sign in Eq.(3.17) means that heat flows from the higher temperature surface to the lower one. For simplicity, only the steady state of one dimension (1D) is considered. Thus Fourier’s law of heat conduction along \( x \) direction (m) can be express as

\[
q = -\lambda_T \frac{\partial T}{\partial x}
\]  

(3.18)

or

\[
\dot{Q} = -\lambda_T A \frac{\partial T}{\partial x}
\]  

(3.19)

where \( q \) is the one dimensional heat flux. The heat transfer rate \( \dot{Q} \) (W) represents the heat flow through a defined cross-section area \( A \) (m²) measured in watts.

\[
\dot{Q} = \int_A q \, dA
\]  

(3.20)

By integrating the 1D heat flow equation through a thickness of material \( d \) (m), yields
\[
\dot{Q} = \frac{\lambda_r A}{d} (T_a - T_b) \tag{2.21}
\]

where \(T_a\) and \(T_b\) are the temperatures (K) at the two boundaries. The thermal conductance of the element \(G_{th}\) (W/K), which is inversely proportional to a thermal resistance \(R_T\), can be defined as \(G_{th} = \frac{\lambda_r A}{d}\) and therefore

\[
G_{th} = \frac{\dot{Q}}{(T_a - T_b)} \tag{3.22}
\]

**Electrical analogy for 1D heat conduction**

Temperature is the driving force or potential for a heat flow. The flow of heat over a heat flow path should then be proportional to the thermal potential difference across the path and the thermal resistance of it, which means heat flow is analogous to electric current flow. The steady state heat flow equation can compare to the Ohm’s law for current through a resistor \(R_{elec}\) as following forms,

\[
\dot{Q} = \frac{\lambda_r A}{d} (T_a - T_b) \quad \leftrightarrow \quad I = \frac{1}{R_{elec}} (V_a - V_b)
\]

therefore, we can draw the analogies as shown in table 3.1 [32].

<table>
<thead>
<tr>
<th>Heat Flow ([\dot{Q}])</th>
<th>Current ([I])</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature Difference ([T_a - T_b])</td>
<td>Voltage Difference ([V_a - V_b])</td>
</tr>
<tr>
<td>Thermal Conductance ([G_{th}])</td>
<td>Electrical Conductance ([G_{elec}])</td>
</tr>
</tbody>
</table>

The electrical to heat conduction analogy leads to applying of circuit theory for understanding and solving heat conduction problems [32]. For instance, as shown in figure 3.3 heat flow through the composited plane with thermal resistance \(R_1\), \(R_2\) and \(R_3\) can be modeled as the lump circuits, then its equivalent resistance, can be determined by circuit theory. However, to avoid complexity caused by non-linearities, the conductivity of materials will be assumed uniform, isotropic and independent of temperature [30].
3.4 Bolometer array operated in atmospheric environment

The performance of modern uncooled bolometer detectors operating in room temperature, have been dramatically improved. Detector array performance, NETD, can reach values as low as 25 mK [29, 33-35]. However to reach such performance, they are required to operate in a high vacuum environment. As shown in paper I, Eq. (2)-(6) and [26], one of the parameters which significantly affect their performance is thermal conductance of bolometer pixel $G$, which relies essentially on the thermal isolation of the membrane from the environment. Due to the heat loss through gases surrounding the bolometer membrane under atmospheric pressure, the thermal conductance $G$ increases dramatically.

In commercial IR cameras, not only overall performance but other factors such as cost of package and detector life time must be considered. High vacuum encapsulation leads to complex packaging and the need for frequent maintenance. A NETD of 80 mK - 200 mK is sufficient for many commercial IR imaging applications [36, 37]. For commercial usage, a possible trade-off between performance and cost, is to operate the IR bolometer in an semi-vacuum environment or even at atmospheric pressure. In addition, an increase of the pressure can also reduce the bolometer self-heating effect since it relates to the thermal conductance $G$ as described in paper I and [38].

To optimize the IR bolometer design under several thermal isolation conditions (i.e. low vacuum), a thermal model of the bolometer arrays is required. In this section, a physical model of the influence of the surrounding environment on the bolometer thermal conductance is presented. The resulting thermal conductance simulations are used in Eq. (1-9) of paper I to predict the performance of detector arrays. The thermal conductance $G$ of a stand-alone bolometer pixel consists of [28]

$$G = G_{\text{leg-conduction}} + G_{\text{radiation}} + G_{\text{gas-conduction}} + G_{\text{convection}}$$

where $G_{\text{leg-conduction}}$ is the thermal conductance due to the heat conduction via its supports, $G_{\text{radiation}}$ is due to membrane radiation, $G_{\text{gas-conduction}}$ is due to heat
conduction via its surrounding gas and $G_{\text{convection}}$ is due to convection by surrounding gas. $G_{\text{radiation}}$ can be written as

$$G_{\text{radiation}} = 2 \cdot 4 \sigma \delta A_m T^3$$

(3.24)

where $\sigma$ is the Stefan-Boltzmann’s constant, $\delta$ is the effective surface emissivity, $2 \cdot A_m$ is the area of the membrane (both the top and bottom surface) and $T$ is the absolute temperature. Assuming that the temperature difference between the membrane and its surrounding is small and in most practical cases, the membrane area is small ($\mu m^2$), thus $G_{\text{radiation}}$ is small compared to the $G_{\text{leg-conduction}}$. Therefore thermal conductance by emitted infrared radiation is negligible [28]. Further, on the small scale, convection through the gases is also considered negligible [28, 29]. The thermal conductance contribution to the total thermal conductance of a bolometer pixel operating in atmosphere can be rewritten as

$$G = G_{\text{leg-conduction}} + G_{\text{gas-conduction}}$$

(3.25)

For pixel operation in a variable atmosphere with a certain bolometer pixel area $A$ and separation $d$ between the bolometer membrane and the substrate, the gas thermal conductance is proportional to the gas thermal conductivity as a function of the ambient pressure [28, 39]

$$G_{\text{gas-conduction}} = \lambda_{\text{gas-p}} \cdot \frac{A}{d}$$

(3.26)

with the assumption that the separation $d$ between the bolometer membrane and the substrate below, is small compare to the distance between the upper membrane surface and the infrared window of the detector arrays package. The thermal conductivity $\lambda_{\text{gas-p}}$ is given by [28]

$$\lambda_{\text{gas-p}} (p,d) = \frac{1}{\frac{1}{\lambda_{\text{gas}}} + \frac{\gamma_{\text{gas}} \cdot p \cdot d}{1}}$$

(3.27)

where $p$ is the pressure of the surrounding gas, $\lambda_{\text{gas}}$ is the pressure-independent thermal conductivity of the gas in the high pressure regime (i.e. $\lambda_{\text{air}} = 0.024 \text{ W/Km}$ for air) and $\gamma_{\text{gas}}$ is the thermal conductivity per unit pressure and length in the low pressure regime ($\gamma_{\text{air}} = 1.9 \text{ m/Ks}$ for air) [28]. Substitute (3.27) in (3.26) gives
\[ G_{\text{gas-conduction}}(p,d) = \frac{A}{\frac{d}{\lambda_{\text{gas}}} + \frac{1}{\gamma_{\text{gas}} \cdot P}} \]  

which means, with different separation \( d \), the gas thermal conductance varies with varying pressure. From Eq. (3.27) with different \( d \) values, the relation between the thermal conductivity and ambient pressure are shown in figure 3.4.

\[ \text{Figure 3.4 Thermal conductivity as function of air pressure and } d. \]

### 3.4.1. Thermal conductance modeling of microbolometer arrays

In this work, a three-dimensional thermal conductance model of bolometers has been developed. The model includes heat flowing from the membrane to the substrate and lateral heat flow from the membrane through the air gap to the legs and also to the neighbouring membranes via the surrounding gas as shown in figure 3.5.

Considering the heat dissipating mechanism in figure 3.5 together with the circuit theory concept, the thermal conductance of the pixel associating with its neighbours can be simply represented as a 1D thermal conductance network as depicted in figure 3.6. To estimate thermal conductance for such complicated features, it becomes convenient to consider them as thermal conductance of overall heat transfer. In this case \( G_{eq} \) represents the average thermal conductance over the heat flow path.

The effect of the environment on the thermal conductance of a bolometer is studied by using a 3D finite element steady state thermal simulation in CMSOL Multiphysic software. In the study, the prototype pixel needs to be defined first. Using the available features and parameter data of the state-of-the-art uncooled
vanadium oxide bolometer from [29, 33] as depicted in table 3.2, the subdomains of the 3-D array model are created. The initial resulting parameter and performance of this studied model are benchmarked with existing published values from [29, 33].

In the model, the detector membrane is suspended by two thin legs and separated from the substrate below by two metal studs (vias). Figure 3.7 show the top view of a detector pixel. The detector arrays are formed by locating the lines of the pixel in two dimensions. In the simulations, the objects are partitioned into a finite number of discrete elements by the software, and then apply the governing heat balance equations to each element. Considering the leg profile, the Ti layer on the leg top is relatively thin compared to the other structures. This becomes problematic since for a very thin object with very large aspect ratio, the software generates many mesh elements in it and at its interface, resulting in higher CPU time and memory demand. To overcome this issue, the thin shell approximation module is used for modeling this special layer. In addition, the arrays are formed by symmetrical detectors, so just one half of the array model was used for simulation. This is useful when CPU and memory are a limiting factor (i.e. when $d$ and pressure increase).
By applying a temperature gradient over two boundaries of heterogeneous objects with known thermal conductivity, one can obtain the heat flux passing through the boundaries. Using Fourier’s law of heat conduction, from Eq.(3.22), the thermal conductance of the media can be calculated by integrating the heat flux over the boundary area (Eq 3.20) and then divide it by the temperature difference at the boundary.

Table 3.2  FEM model feature and material parameter.

<table>
<thead>
<tr>
<th>Geometric feature</th>
<th>Geometric material conductivity $\lambda$(W/Km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Membrane:</td>
<td></td>
</tr>
<tr>
<td>area (A)</td>
<td>18 X 27</td>
</tr>
<tr>
<td>thickness</td>
<td>1</td>
</tr>
<tr>
<td>Membrane</td>
<td>Si, $\lambda$$_{Si} = 148$</td>
</tr>
<tr>
<td>Leg:</td>
<td></td>
</tr>
<tr>
<td>area (width X length)</td>
<td>1 X 56</td>
</tr>
<tr>
<td>thickness top layer</td>
<td>0.01</td>
</tr>
<tr>
<td>down layer</td>
<td>0.5</td>
</tr>
<tr>
<td>Leg layer:</td>
<td></td>
</tr>
<tr>
<td>top layer</td>
<td>SiN, $\lambda$$_{SiN} = 3.2$</td>
</tr>
<tr>
<td>down layer</td>
<td>Ti, $\lambda$$_{Ti} = 21.9$</td>
</tr>
<tr>
<td>Vias:</td>
<td></td>
</tr>
<tr>
<td>area</td>
<td>1 X 1</td>
</tr>
<tr>
<td>height (separation $d$)</td>
<td>3-12</td>
</tr>
<tr>
<td>Vias:</td>
<td></td>
</tr>
<tr>
<td>array gas filling</td>
<td>Air, $\lambda$$<em>{air-p} = \lambda$$</em>{gas-p}(p,d)$, $\lambda$$_{air} = 0.024$</td>
</tr>
<tr>
<td>Pixel gap:</td>
<td></td>
</tr>
<tr>
<td>wide-side</td>
<td>1</td>
</tr>
<tr>
<td>longitudinal-side</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Figure 3.7  Drawing of pixel top view.
3.4.2 Simulation result and array performance effect

To evaluate the reliability of the model under vacuum conditions, the object geometry and thermal material parameter from the Table 3.2 was used resulting in a thermal conductance $G$ that is comparable to published values. At a vacuum level of 0.001 mbar, the $\lambda_{\text{gas-p}} = 5.7 \times 10^{-7}$ W/Km (figure 3.4) yields $G_{\text{gas-p}} = 3.8 \times 10^{-8}$ W/K which correspond to the $G$ value of the published bolometer $G = 3.7 \times 10^{-8}$ W/K (from table 1 in paper I).

In high pressure environments, heat can flow from the membrane via the gas to the legs (figure 3.8), resulting in a modification of the $G_{\text{leg}}$ value in the high pressure regime. Also under ambient pressure, the model is created in $9 \times 9$ arrays in order to indentify which of the surrounding pixels contribute to the $G$ of the considered pixel. The result shows that the $G$ of a bolometer pixel is mostly influenced by the neighbouring pixels as depict in figure 3.9a. The resulting temperature profile comparison of figure 3.9 b and c illustrates that heat flows across the air gap easier in the longitudinal direction which means that the nearby membranes on the longitudinal side are more influenced by the heated detector pixel.

Figure 3.8 Top view of a bolometer leg with parts of the bolometer membrane and a substrate connection (Tb) including the heat flow paths.

Figure 3.9 FEM simulation of gradient temperature a) 3D b) cross section along wide side  c) cross section along the longitudinal side.
A model analysis based on the circuit model in figure 3.6 is discussed in the following. In contrast to the stand-alone bolometer pixel model, the array model has the thermal links from pixel to pixel represented by $G_{\text{gap,lat}}$, which is proportional to the operational pressure and the gap between the pixels. Given that the gap is constant, when the arrays are operated in the high vacuum, $G_{\text{gap,lat}}$ is relatively low, so the effect of the thermal conductance from neighbouring pixels is negligible. But when operated in low vacuum, $G_{\text{gap,lat}}$ becomes significantly higher, which allows the heat flow from one pixel to the neighbouring pixel result in a thermal conductance change and reducing of the sensitivity. $G_{\text{gap,lat}}$ is reversely proportional to the gap. However, to achieve a high array fill factor, the gap should be as narrow as possible for practical cases.

For any given gap and constant pressure, the resulting thermal conductance decreases dramatically when increasing the distance $d$. A graph of the simulated thermal conduction $G_{\text{eq}}$ between the bolometer pixel and its surroundings, in dependence of the distance $d$ operating in atmospheric pressure ($\lambda_{\text{gas-p}} = \lambda_{\text{air}} = 0.024 \text{ W/Km}$), is shown in figure 3.10. The two curves show $G_{\text{eq}}$ of two different gap distances of $1 \mu m$ and $2 \mu m$ between the bolometer and the neighboring bolometer membranes. It can be seen that the influence of neighboring bolometer membranes on $G_{\text{eq}}$ becomes constant when the distance $d$ increases.

Using $\lambda_{\text{gas-p}}$ from the graph depicted in figure 3.4 as a thermal conductivity of the gas environment in the simulation model, the simulated $G_{\text{eq}}$ of the bolometer is shown in figure 3.11a. The figure shows $G_{\text{eq}}$ of the bolometer operating under pressure variations and compares the analytically calculated conductivity of a stand-alone bolometer pixel.

![Figure 3.10](image.png)

*Figure 3.10* Simulation results of the thermal conduction between a bolometer and its surroundings in dependence of the distance $d$ between the bolometer membrane and the substrate. The two curves represent two different gap distances between the bolometer and the neighbouring bolometer membranes.
Once a bolometer conductance $G_{eq}$ is calculated, the performance of an detector array under varying pressure can be determined by using Eq.(1-9) and the parameters in paper I. Figure 3.11b shows the NETD of a bolometer array as a function of pressure with different separations $d$.

### 3.5 Discussion

The resulting simulation shows that when increasing the gas pressure, $G_{eq}$ of a bolometer pixel is influenced by the neighboring pixels. At atmospheric pressure, figure 3.10 indicates that a thermal conduction of $G = 4 \times 10^{-6}$ W/K between the bolometer and its surroundings seems feasible when using distances $d$ between the bolometer membrane and the substrate of 7.5 μm and 6.5 μm together with gap distances between the bolometer and the neighbouring bolometer membranes of 1μm and 2 μm, respectively.

![Figure 3.11](image-url)  
**Figure 3.11**  
(a) Resulting simulation total thermal conduction between a bolometer and its surrounding in dependence of the gas pressure  
(b) Resulting Calculation of bolometer system NETD in dependence of the gas pressure using $G_{eq}$ data from a).
4 3D integration for infrared bolometer arrays

4.1 Introduction

A modern IR detector array is commonly comprised of two parts. First is a transducer for transferring the IR radiation to an electrical signal. The second part is the CMOS circuit on which normally the transducer is mounted. At present, the most preferable technique for manufacturing a small detector array of uncooled bolometers is by monolithic integration. The monolithic thermal isolation structure typically offers a lower thermal conduction than the indium bumps in the hybrid structure. In monolithic bolometer integration, conventionally, the first step is to deposit a sacrificial layer which is utilized for defining the membrane-substrate distance. Thin film of silicon nitride (SiN) layer (less than 1 μm) is deposited on the sacrificial layer to form a membrane and legs of the detector. The temperature sensitive resistor material is deposited on the SiN layer for temperature detection and for a electrical bias connection. The membrane is free-standing and suspended by two legs after the sacrificial layer is removed. Figure 4.1 illustrates the schematic structure of a monolithic transducer structure on the CMOS circuit wafer. The monolithic integration is relatively simple and cost efficient.

In resistive IR thermal detectors, the transducer is typically made of a high TCR material, which requires particular equipment or treatment for the deposition process. For instance, vanadium oxide (TCR of 2-3%/K) which is extensively used for microbolometers, is not a standard material and requires a special technique for the material preparation. For monolithic integration of high TCR transducers on top of a CMOS circuit, the processes are limited to temperatures below 450°C due to the limited temperature budget of standard IC technology [40-43].

![Figure 4.1 A MEMS transducers on the top of a CMOS circuit.](image-url)
4.1.1 Transfer bonding for bolometer FPAs

Since the limited temperature budget limits the material selection for CMOS integrated MEMS, we have used a transfer bonding technique based on adhesive wafer bonding. In this scheme, a bolometer material wafer and a CMOS wafer are manufactured separately before they are merged together [44, 45]. The fabrication of IR bolometer arrays using transfer bonding have been reported in [46, 47].

Figure 4.2 Fabrication process flow of infrared bolometer arrays using transfer bonding: a) Two wafers are implemented independently b) bond resist coating and subsequent wafer bonding c) membrane definition d) SiN layer deposition e) via hole definition f) via hole patterning g) metal contract definition h) leg patterning.
Figure 4.2 shows the process steps of adhesive wafer transfer bonding based on monolithical 3D integration of IR bolometer detectors. All process steps are performed at temperatures below 450°C.

The temperature sensitive layer on the transducer (donor) wafer and the CMOS (target) wafer are implemented independently before they are bonded together as depicted in figure 4.2a. The sequence starts with spinning the intermediate resist on the CMOS wafer. The resist layer thickness is used to define the separation distance between the bolometer membrane and the substrate. The wafer pairs are then bonded adhesively together (figure 4.2b). The donor wafer is thinned down to the etch-stop layer. Thereafter the detector membrane feature is defined as shown in figure 4.2c with the schematic top view on the upper-right part. In figure 4.2d, a leg material layer (i.e. SiN) is deposited on the top layer. Next, the process in figure 4.2e is used to define via holes by etching (RIE etching for SiN) into the leg material and through the buried resist layer below. The metal studs (vias) are formed in the via hole patterns by electroplating. In figure 4.2g, the electrical via contact holes are defined on the top of the membrane and then an electrical via contact layer is deposited (i.e. by Ti sputtering) to connect electrically the membrane and the vias. After defining the legs and the pixel features, the pixel is released by removing the bonding resist with oxygen plasma. Now the detector membrane and its legs are only supported by two small metal studs (vias). An example of a 3D integrated detector array is shown in figure 4.3.

4.2 Polymer as a bonding intermediate in 3D integration

In adhesive wafer bonding a polymer layer is used as the intermediate bonding material. Adhesive wafer bonding has been used for the fabrication of three-dimensional ICs (3D-ICs), advanced microelectromechanical systems (MEMS), bioMEMS, heterogeneous 3D integration of MEMS and ICs. The intermediate bonding material is often used to define the substrate to substrate distance. In many applications, the device parameters are significantly influenced by such
distances (i.e. non-uniformity, surface roughness). In micro-mirrors, for instance, the arrays require a very flat surface to achieve a high optical quality. A number of adhesives are available (i.e. BCB, thermoplastic polymers). However, in order to control the effects from the intermediate layer, the most process and application compatible adhesive should be selected. Thus, a characterization of the intermediate adhesive is essential. In general, for 3D MEMS integration, the requirements on the bonding adhesive characteristics are:

- Create void-free and strong wafer bonds.
- Suitable for sacrificial removal in a pure oxygen plasma.
- Withstand post bonding temperatures of more than 130ºC.
- Create bond interfaces with highly uniform adhesive layers thickness (e.g. for micro-mirror and infrared bolometer applications).

From the IR FPA fabrication point of view, the intermediate adhesive material has a key role on the fabrication yield as the adhesive is used to define the gap of the free-standing detection element array.

### 4.2.1 Nano-imprint resist in 3D integration of bolometer

Based on paper II, the following sections introduce investigations of nano-imprint resist series mr-I 9000 as adhesive wafer bonding material for MEMS 3D integration, particularly for IR bolometer arrays. The nano-imprint resist series mr-I 9000 is a commercially available thermosetting (cross-linking) material supplied as a polymer precursor with a cross-linking level of about 75 %. Its polymer precursor is dissolved in a solvent and available in various viscosities for spin-coated layer thicknesses from 100 nm to 2500 nm. These nano-imprint resists have a low viscosity at about 80 ºC and their cross-linking level and viscosity significantly increase at temperatures of about 150 ºC and gradually reduce the ability of the resist coatings to deform [48-50]. Due to their material and curing properties they are adapted to the requirements of nano-imprinting [51]. These properties are to a large extent the same properties that are also needed in adhesive wafer bonding.

### 4.2.2 Experiment and evaluation of material

This study is performed using a standard adhesive wafer bonding scheme shown in figure 4.4 suitable for thermosetting adhesives. The curing temperatures and times in the wafer bonding scheme are selected to be in line with the recommended curing temperatures from the material data sheets of the nano-imprint resist supplier.
In our experiments, 500 µm thick and 100 mm diameter, single-sided polished silicon wafers are bonded to 300 µm thick and 100 mm diameter silicon wafers. The 300 µm thick silicon wafers are double-sided polished and contain a 600 nm thick layer of thermally grown SiO2 on each.

Figure 4.5 shows the process scheme that is used to evaluate the polymer bond interface and the polymer layer thickness of wafers bonded with nano-imprint resists with different resist pre-curing levels (optional in step c). The details of
experimental parameters are shown in table 4.1. The result of thickness measurements of two nominal adhesive resist are compared in the figure 4.6. Additional experiments were done to demonstrate the suitability of the nono-imprint resist for bonding of wafer with surface topographies. In this experiment, the surface topographies with a height of 50 nm are created on one wafer of the wafer pairs as shown schematically on the left part of the lower wafer in figure 4.5. The nominal adhesive thickness was 300 nm. The experiment is done by adhesive

<table>
<thead>
<tr>
<th>Adhesive resist thickness (nm)</th>
<th>Pre-curing</th>
<th>Thickness measurement &amp; Visual inspection</th>
</tr>
</thead>
<tbody>
<tr>
<td>2500</td>
<td>a) no pre-curing</td>
<td>thck. meas.</td>
</tr>
<tr>
<td></td>
<td>b) 160°C 30 min</td>
<td>thck. meas.</td>
</tr>
<tr>
<td></td>
<td>c) 180°C 30 min</td>
<td>thck. meas.</td>
</tr>
<tr>
<td>300</td>
<td>a) no pre-curing</td>
<td>thck. meas. &amp; Visl inspc.</td>
</tr>
<tr>
<td></td>
<td>b) 150°C 30 min</td>
<td>thck. meas.</td>
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<tr>
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<td>c) 160°C 30 min</td>
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Figure 4.6  Thickness measurements after wafer bonding a) with two nominal 2500 nm thick nano-imprint resist layers b) with two nominal 300 nm layers.

wafer bonding as shown in figure 4.4 without pre-curing in step c, and evaluated by the process shown in figure 4.5. The result from inspection through the thin SiO₂ layer is shown in figure 4.7.

The results show that, for a given nominal thickness, a pre-curing process has influence on the surface uniformity. Void formation occurs when the cavities or trenches can not be completely filled with the polymer adhesive.
Figure 4.7 Local micro-void formation when bonding wafers with 50 nm high structures.
5. Room temperature packaging

5.1 Introduction to MEMS packaging

Micro packaging is essential for industrial applications in the field of MEMS. The MEMS packaging is the most expensive and time consuming step in overall MEMS production. The cost of MEMS packaging and testing have traditionally been greater than 80 percent of the total cost of the product and could be ten times that of the component itself [52].

Although MEMS fabrication uses processes and tools developed for the microelectronic industry with some modification, the MEMS design is quite different from its microelectronic counterpart because every specific MEMS device function plays an important role in the package design consideration. For example, resonant devices such as RF filter might require a vacuum packaging while accelerometers might work better at pressure that is close to atmospheric pressure. This makes the development of packaging standards for MEMS almost impossible. Therefore, packaging and package design must be closely coupled with the system and device design.

As MEMS devices often contain fragile parts and some require operation in a controlled atmosphere, standard packaging technologies of integrated circuits cannot be directly used for MEMS devices. For instance, die sawing or injection molding process of plastic package will cause damage to movable parts if they are not protected. Besides cost and process optimization, the MEMS packaging technology must consider the following issues [53]:

1. The microstructure and its processing electric circuits must not be damaged by the packaging process;
2. it should be applicable to different MEMS processes;
3. it should be based on the existing IC packaging to reduce cost;
4. and it should satisfy requirement of MEMS devices such as hermetic vacuum sealing.

5.2 Wafer-level packaging

In the past, device level packaging has been used in packaging with traditional metallic and ceramic packages, such as the dual in line packaging (DIP) shown in Figure 5.1. A device had first to be separated (i.e. diced) from its wafer before it could be put into a package. This type of packaging is reliable but costly. The problem is that handling of the movable MEMS parts will cause damage, affecting the yield significantly. Recently, the wafer level package (WLP) has become one of
the dominant packaging technologies due to its advantages such as fewer processing steps (figure 5.2), lower cost, and enhanced device performance compared to single chip packages [54]. WLP packaging is performed while the device remains on the wafer. Then the devices are separated by sawing or other means as shown in figure 5.3. Wafer-level packaging is expected to provide a number of benefits such as smaller system size, interconnection from IC to printed wiring boards (PWD), packaging cost reduction, testing cost reduction, burn in cost reduction and electrical performance improvement.

Many MEMS sensor devices are sensitive to contamination, ambient pressure, and other environmental factors. To protect them from malfunction, the device package must be hermetically sealed. Wafer-level hermetic cavity packaging provides potential cost, handling and performance advantages in packaging of MEMS. As the cavities grow smaller, whereas the technical challenges grow larger, these lead to development of many technical approaches in the field. The
package must satisfy the following requirements: a cavity, a cap to protect fragile MEMS parts, strong bonding for hermeticity, a low cost wafer packaging and batch process, low temperature processes, and a simple fabrication process [53, 54].

Figure 5.3 A wafer-level packaging process. The cavities are implemented by wafer bonding and finally they are separated by dicing blade cut through the wafer.

Figure 5.4 A wafer-level packaging by thin film deposition: a) MEMS device b) deposition of sacrificial layer on device and substrate c) deposition of sealing layer, subsequently etch hole opening d) removing of the sacrificial layer, subsequently encapsulation of the cavity (adapted from [59]).

Wafer-level Vacuum packaging has been implemented in two main different ways.

- **Wafer bonding processes**
  Bonding of a cap wafer in a vacuum environment is used to vacuum package MEMS devices [55-58]. The concept of wafer bonding cavity sealing (including device separation process) is depicted in figure 5.3.

- **Integrated processes (Deposition of a thin film)**
  After fabricating the devices, a thin film is deposited in combination with a sacrificial layer to package the desired devices [59]. Figure 5.4 shows the thin film deposition process sequences.

To date commonly used wafer-level bonding techniques for manufacturing of micro-cavities are solder bonding [55], eutectic bonding [56], thermocompression bonding [57] and adhesive wafer bonding [58]. Solder and eutectic bonding techniques typically require elevated temperatures of 100 to 400 °C and the oxides at the metal surfaces need to be removed using e.g. flux or other methods. Eutectic bonding requires very flat surfaces to achieve consistent bonding results over large areas. Thermocompression bonding typically requires flat bonding surfaces in combination with elevated temperatures and high bonding pressures. Polymer
adhesives are typically not suitable for manufacturing of hermetically sealed cavities, since polymers are permeable to gases [60]. Most MEMS and IC circuit device are sensitive to high temperatures. Thus, the issue of protection of microstructures, circuits, and interconnects requires that the packaging should be done at low temperatures.

5.3 Room temperature micro-cavity sealing for bolometer arrays.

Bolometer thermal imaging arrays need to be operated in a controlled atmosphere to achieve a good sensitivity [28, 39]. To reduce the cost of the IR imaging chip, a wafer level packaging approach is proposed for detector manufacturing.

Gas molecules that are absorbed in the surfaces of the substrates can outgas and contaminate the atmosphere inside the micro-cavities if the wafers are heated during the bonding process [61]. In addition, a low-temperature packaging process can avoid damage of the detector CMOS circuit. These problems affect on the life time and yield of the product. To deal with such problems, a room temperature sealing technique can be applied for IR detector packaging.

In this thesis, a room temperature metal to metal bonding technique is introduced for creation of hermetically sealed micro-cavities for bolometer arrays in commercial IR cameras. The proposed cavity sealing method is based on plastic deformation of the metal sealing rings at the interfacial areas. This approach is performed by IC standard and out-gassing free processes, such as electroplating and room temperature bonding.

5.3.1 Cold welding conceptual packaging

Cold-welding is a process performed at room temperature to join two metals together. Using mechanical force or pressure, two metallic surfaces in intimate contact are pressed together until interatomic forces are developed to complete the weld, while considerable plastic deformation is taking place. When sufficient load is applied to a metal or other object material, the material will change in shape. This change in shape is called deformation. If the object returns to its original shape after the force is removed, it is an elastic deformation (stress-strain values are in elastic region as shown in figure 5.5).
Figure 5.5  A stress–strain curve of a ductile material. The linear slope part of the curve is the elastic region. Beyond the elastic limit point, further increase in load yields very large increases in strain. This is the plastic region.

Figure 5.6  (a) Top view of micro-cavities with metal sealing rings on wafer 1 and corresponding metal sealing rings on the wafer 2. (b, c) Schematic cross-sectional view of the wafers with corresponding metal sealing rings before (b) and after (c) bonding. (d) 3D view of the overlaying sealing rings of an aligned and bonded wafer pair.
When the stress is sufficient to permanently deform the metal, the metal does not return to its original shape after removing the force, thus this is called plastic deformation (stress-strain values fall in plastic region). Plastic deformation involves the breaking of a limited number of atomic bonds by the movement of dislocations.

In paper III, we propose a method for wafer-level sealing in which, corresponding metal sealing rings are located on the two wafer surfaces to be bonded. The two wafer surfaces with the corresponding and slightly overlapping sealing rings are aligned and pressed to each other. The resulting bonding pressure causes high shear and compressive strains and then plastic deformation at the interfacial areas of the corresponding metal rings occur, thus enabling cavity sealing at room temperature. Figure 5.6a shows a schematic top view of a first wafer (wafer 1) with cavity structures and the corresponding rings on the second wafer (wafer 2). Figure 5.6b shows a schematic cross-sectional view of a wafer pair containing corresponding metal sealing rings that define the cavities. Figure 5.6b shows the wafer pair before and Figure 5.6c after the wafer pair is aligned and brought into contact. When the wafers are properly aligned to each other, the corresponding metal sealing rings have small overlapping areas. The wafer pair is pressed together by applying a uniform force. The corresponding metal sealing rings wedge into each other as indicated in figure 5.6d. This is due to the creation of large local shear and compressive strains at the overlapping edges of the metal sealing rings, resulting in localized plastic deformation and cold welding. The process must be done in a pressure controlled chamber to obtain the desired pressure (i.e. vacuum) inside the cavities after bonding.

5.3.2 Sealing rings

In the experiments, electroplated gold was selected as metal for the sealing rings that define the micro-cavities because gold is a relatively soft and deformable material. As shown in figure 5.7, the metal sealing rings are manufactured by sputtering a thin gold seed layer on the wafers. Next, a thick photoresist layer (> 30 µm) is coated and patterned, and thereby defines the areas for the sealing rings. Gold is electroplated at the areas where the photoresist is patterned (removed) and thus, the photoresist is functioning as a mold for the electroplated gold. Subsequently, the photoresist mold and the gold seed layer are removed with wet-etching processes and the wafers are rinsed with de-ionized water and dried. A scanning electron microscope (SEM) image of the cross-section of an electroplated gold sealing ring is also shown in the last picture of figure 5.7. More details about different sealing ring features, cavity shapes, number of sealing rings are described in paper III.
5.3.3 Experiments and evaluation of cavity sealing

Experiments

The experiments are designed to investigate what influence parameters such as shape, overlap length, number of sealing rings and bonding pressure have on the sealing effect. The sealing experiments have been performed by two experimental schemes. In the first experiment, glass to Si wafer bonding was used and in the second SOI to Si wafer bonding was used. All wafer bonding experiments were done in a wafer bonder, with a vacuum level of $1.00 \times 10^{-4}$ mbar in the bonding chamber.

Before the sealing structure on one wafer and its corresponding sealing structure on the second wafer are bonded to each other, they must be aligned properly. For alignment of glass to Si wafer pairs, the aligned structures are inspected through the top glass wafer. Then bonding can be done after the normal (front-side) alignment process. For alignment of SOI to Si wafers, the front-side alignment procedure is not possible, since the wafer pairs are not transparent. In this case, back side alignment is employed. Thus, by cloning the position of the alignment mark structures to the backside of one wafer, the alignment is possible. The alignment steps are depicted in figure 5.8.

- First, the gold structures on the wafer front side are protected by a thermal release tape. Then a thin layer of photoresist is deposited on the backside of the silicon wafer as shown in figure 5.8a.
- In figure 5.8b, the original mask is loaded into the bond aligner. An image of the alignment marks on the mask is digitized and stored. The wafer is loaded in between the mask and microscope where the wafer back side is facing the

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Figure 5.7 Manufacturing of sealing ring by electroplating process.
original mask. Consequently, the alignment marks on the front side of wafer a are aligned to the alignment marks on the digitized image.

• As shown in figure 5.8c, the features on the mask are transferred onto backside of wafer a by UV light exposure, and development.

• In figure 5.8d, we load wafer b, with its front side facing the bond interface, into the bond aligner. We then digitize and store its front side image, thereafter load wafer a with its front side facing the bond interface, under the wafer b. The transferred features (including alignment mark features) on the backside of wafer a are aligned to the alignment marks of wafer b on the digitized image.

• After wafer alignment, the bond structures on both wafers are bonded by application of a bond pressure as shown in figure 5.8e.

After bonding, the bonded silicon-glass wafer pairs are evaluated with a gross-leak test method to investigate the cavity seal quality. In the gross leak tests, isopropanol alcohol (IPA) is injected in the 30 \( \mu m \) to 40 \( \mu m \) wide gap in between the bonded wafer pair. Liquid and vapor IPA are able to enter the cavities that contain gross leaks. As shown in Figure 5.9, liquid and vapor leakage into the cavities are visually detected through the glass wafer by microscope inspection. Condensation of IPA vapor inside a cavity that contains a gross leak is shown in Figure 5.10.

![Figure 5.8 Illustration of backside alignment process a) wafer-backside coating with photoresist b) alignment for backside pattern transferring c) exposing and developing of backside patterns d) alignment of two wafer using backside patterns and front side digitized image e) wafer pairs bonding.](image-url)
Evaluation

In the evaluation process of bonded silicon-SOI wafer pairs, the bulk silicon of the SOI wafer of the wafer pair need to be thinned down to enable the thin Si membrane to be deflected by the pressure difference between inside and outside of the cavity. The bulk silicon layer is removed by using deep reactive ion etching (DRIE) using the SiO$_2$ layer as the etch stop as shown in figure 5.11a. There are two different evaluation steps for these wafer pairs.

After the thinning process, only the 20 µm thick silicon device layer together with the 1 µm thick SiO$_2$ layer remains as lid on the sealed cavities. The pressure difference between inside and outside of the cavity changes the deflection of the Si/ SiO$_2$ membrane (figure 5.11b). An image of a micro-cavity with a deflected membrane to the inside of the cavity is shown figure 5.12a. To evaluate the encapsulated atmosphere inside the micro-cavities, the wafers are placed in a variable vacuum pressure chamber with a glass window. When lowering the gas pressure in the vacuum chamber, the cavity membranes are deflected upwards and the leveling of the cavity membranes is confirmed by visual observation through the glass window of the vacuum chamber. Leveling of the micro-cavity membranes happened for most cavities at pressure levels on the order of 5 mbar to 10 mbar.

A basic model for the deflection of the cavity membrane has been used to verify the estimated pressure range inside the cavities. Cavity membranes are deflected by the difference in pressure $\Delta P$ between the outside of the cavities (atmospheric pressure $P_{\text{atm}}$) and the inside of the cavities (cavity pressure $P_{\text{vac}}$). Thus, the cavity pressure relative to ambient atmospheric pressure can be estimated from $P_{\text{vac}} = P_{\text{atm}} - \Delta P$ where $P_{\text{atm}} = 1013$ mbar. To estimate large load-deflections of flat, circular diaphragms ($y_0 < h/2$), the analytical expression

$$\frac{\Delta P a^4}{Eh^4} = \frac{16}{3(1-\mu^2)} \frac{y_0}{h} + \frac{7-\mu}{3(1-\mu)} \frac{y_0^3}{h^3}$$

(4.1)

can be used [62], where $h$ is the membrane thickness, $E$ is the Young’s modulus, $\mu$ is the Poisson’s ratio, $a$ is the diaphragm radius and $y_0$ is the center deflection of the diaphragm. The resulting center deflection of the membranes from the circular cavities (3500 µm diameter) was measured with a profilometer to be about 40 µm, excluding offset deflection from the SiO$_2$ strain as depicted in figure 5.12b with a silicon membrane thickness of 20 µm (excluding the 1 µm thick SiO$_2$ layer).

Sealing of micro-cavities has been achieved by using a room temperature wafer bonding process. The estimated pressure difference $\Delta P$ can be calculated to be on the order of 970 mbar. Thus, the estimated gas pressure inside the cavity would be on the order of 40 mbar, which is in line with the estimates from the cavity membrane deflection evaluation inside a vacuum chamber.
Figure 5.9 Microscope Inspection through the top glass wafer to be able to observe bond interface and gross-leak inside a cavity. The isopropanol alcohol (IPA) is injected in the 30 µm to 40 µm wide gap in between the bonded wafer pair.

Figure 5.10 View through the top glass wafer at the bond interface of a cavity. Three sealing rings with rounded corners on the silicon wafer and the corresponding two sealing rings on the glass wafer are shown. The inside of the cavity contains color traces from isopropanol alcohol vapor that has penetrated the cavity during a gross-leak test.

Figure 5.11 (a) The bulk silicon of the SOI wafer is thinned down with DRIE. (b) Differential pressures between the inside and the outside atmospheres of the micro-cavity cause the thin silicon lid membranes to deflect.

Figure 5.12 (a) Image of sealed circular micro-cavities (diameter of 3500 µm) with the lid membranes bending to the inside of the cavities. (b) Surface profilometer scan of circular diaphragm deflection.
6 Summaries of the appended papers


This paper presents a comprehensive calculational model for the noise equivalent temperature difference (NETD) of infrared imaging systems based on uncooled bolometer arrays. The equations are presented in a new and convenient form. The NETD model is validated and benchmarked using published performance data of a state-of-the-art uncooled infrared bolometer array. The NETD model is used to evaluate possible system and bolometer design improvements.

Paper II. Wafer Bonding with Nano-Imprint Resists as Sacrificial Adhesive for Fabrication of Silicon-On-Integrated-Circuit (SOIC) Wafers in 3D Integration of MEMS and ICs.

This paper presents the use of thermosetting nano-imprint resists in adhesive wafer bonding. The presented wafer bonding process is suitable for heterogeneous three-dimensional (3D) integration of MEMS and integrated circuits (ICs). Detailed adhesive bonding process parameters are presented to achieve void-free, well defined and uniform wafer bonding interfaces. Experiments have been performed to optimize the thickness control and uniformity of the nano-imprint resist layer in between the bonded wafers.

Paper III. Room-Temperature Sealing of Micro-Cavities by Cold Metal Welding.

This paper presents a novel wafer-to-wafer attachment and sealing method for wafer level manufacturing of micro-cavities using a room temperature bonding process. The proposed attachment and sealing method is based on plastic deformation and cold welding of overlapping metal rings to create metal-to-metal bonding and sealing. In addition, wafer-level vacuum sealing of micro-cavities is demonstrated when bonding a silicon wafer to another silicon wafer with the proposed room-temperature sealing and bonding technique.
7 Conclusions

This thesis presents research on essential parts of the design and manufacturing of infrared thermal detectors. Different concepts that can contribute to development of more cost efficient IR cameras have been investigated.

A 3D simulation model for the array thermal conductance has been created. The model analysis has shown that with an increased distance between the bolometer membrane and the substrate, it is possible to operate the array in low vacuum while maintaining reasonable thermal conductance and NETD values.

A study has been made of materials for the adhesive bond layer. The pre-bonding and bonding process parameters of two different thickness of nanoimprint resist layer have been investigated and demonstrated. Thermosetting nanoimprint resists have shown suitability as adhesives for wafer bonding in manufacturing of SOIC wafers for heterogeneous 3D integration of bolometer detector arrays.

A low temperature packaging technique has been investigated. Room temperature wafer-level packaging based on cold welding has been demonstrated and is in principle applicable to IR detector packaging. The proposed process uses standard MEMS processes and equipments and can provide sealed cavities with a room-temperature process.
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References


Integration and packaging concepts for infrared bolometer arrays


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