Towards 17 μm pitch heterogeneously integrated Si/SiGe quantum well bolometer focal plane arrays

Per Ericsson^a, Andreas C. Fischer^b, Fredrik Forsberg^b, Niclas Roxhed^b, Björn Samel^a, Susan Savage^a, Göran Stemme^b, Stanley Wissmar^a, Olof Öberg^a, Frank Niklaus^b

^aAcreo AB, Electrum 236, SE-164 40 Kista, SWEDEN

^bKTH-Royal Institute of Technology, MST, SE-100 44 Stockholm, SWEDEN

ABSTRACT

Most of today's commercial solutions for un-cooled IR imaging sensors are based on resistive bolometers using either Vanadium oxide (VOx) or amorphous Silicon (a-Si) as the thermistor material. Despite the long history for both concepts, market penetration outside high-end applications is still limited. By allowing actors in adjacent fields, such as those from the MEMS industry, to enter the market, this situation could change. This requires, however, that technologies fitting their tools and processes are developed. Heterogeneous integration of Si/SiGe quantum well bolometers on standard CMOS read out circuits is one approach that could easily be adopted by the MEMS industry. Due to its mono crystalline nature, the Si/SiGe thermistor material has excellent noise properties that result in a state-of-the-art signal-to-noise ratio. The material is also stable at temperatures well above 450°C which offers great flexibility for both sensor integration and novel vacuum packaging concepts. We have previously reported on heterogeneous integration of Si/SiGe quantum well bolometers with pitches of 40 μm x 40 μm and 25 μm x 25 μm . The technology scales well to smaller pixel pitches and in this paper, we will report on our work on developing heterogeneous integration for Si/SiGe QW bolometers with a pixel pitch of 17 μm x 17 μm .

Keywords: bolometers, heterogeneous integration, SiGe, quantum wells, focal plane arrays, uncooled IR

1. INTRODUCTION

Due to its relatively high cost, long wavelength infrared imaging has traditionally been the privilege of military and governmental users. However, due to its ability to see the radiation emitted by warm objects without external illumination, or to perform contactless temperature measurements, there is a plethora of applications that could benefit from low-cost infrared imaging solutions. Consumer market applications such as night vision enhancement systems for cars[1] are slowly becoming available, but the market penetration is still limited to high end models from premium brand manufacturers. For this particular application, only a significant reduction in price will enable fleet-wide uptake of infrared imaging systems.

The cost of uncooled long wavelength infrared imaging systems today mainly consist of the cost of the sensor array itself, the cost of packaging and the cost of the lens system[2]. The three areas are highly interlinked and only by considering all three together, a true low-cost solution can be obtained. One of the main trends today followed by all sensor chip manufacturers is to reduce the pixel pitch. By reducing the pixel pitch of the sensor array, at least two benefits relating to price are obtained: more sensor arrays can be manufactured on the same starting wafer reducing the price for each individual array, secondly, a smaller array size for a given resolution leads to a reduction of the size, and thereby the material consumption, of the optics due to the reduced image field. The cost of the raw materials used in the optics is a significant part of the total cost for the lens system, and a reduction of material used directly influences the total cost of the optics.

Reducing the size of each pixel comes at a price, however. The performance in terms of noise equivalent temperature difference (NETD) is inversely proportional to the area of each pixel[3-5]. As the pixel pitch is reduced, it thus becomes increasingly important to optimize each aspect of the bolometer design to retain as much of the performance as possible. For a given pixel pitch, there are several design issues relating to both the sensor material and the sensor-to-ROIC

integration process that must be considered to reach overall good performance. We have previously reported on some aspects of sensor material design and optimization [6,7] and on the integration process for 25x25 μm pitch pixels[8-10]. In this paper we will address further design aspects of the infrared absorbing internal quarter wave cavity and present the latest results on scaling of the heterogeneous integration process down to 17x17 μm pitch bolometer arrays.

2. QUANTUM WELL SENSOR MATERIAL

The thermally sensitive material in the bolometer design under consideration is based on a multi-layer structure of alternating Si and SiGe layers. Due to the narrower bandgap of SiGe compared to Si, and the fact that the bandgap difference between Si and SiGe results in a band discontinuity mainly in the valence band[11-13], the SiGe layers form potential wells for holes travelling perpendicular to the SiGe planes (Figure 1).

Figure 1. Illustration of band line-up for a SiGe layer embedded between two Si layers. The band gap difference between Si and SiGe mainly results in an offset of the valence band edges for Si and SiGe. The hashed line in the figure represents the ground state shift for narrow wells. For well widths above 8 nm, no significant shift is expected[6].

Holes travelling perpendicularly to the SiGe layer plane will be trapped in the well and subsequently reemitted. The emission process is thermally activated resulting in a temperature coefficient of resistance according to Equation 1.

$$TCR(T) = \frac{E_a}{k_B T^2} \quad [K^{-1}] \quad (1)$$

Here, TCR is the temperature coefficient of resistance, E_a the energy barrier height, k_B the Boltzmann constant and T the absolute temperature. The Ge fraction in the well directly affect the energy barrier height and a TCR value of approximately 3%/K is obtained for 32% Ge.

The thermistor is also part of the optical quarter wave cavity that is used to achieve high infrared absorption. Figure 2 shows a schematic illustration of the bolometer concept. The thermistor layer is encapsulated by a resistive film on the top surface and a reflector on the bottom surface. The cavity thickness is chosen to maximize infrared absorption of the bolometer for the wavelength range of interest. The resistive film is needed to match the impedance of the bolometer to the vacuum impedance of the impinging wave.

Figure 2. A bolometer with an internal optical cavity where the cavity is formed by the Si/SiGe thermistor multi-layer structure itself. Due to the relatively high refractive index of Si, the total thickness of the cavity is only 0.6 μm .

To optimize the design of the quarter wave cavity, we have built an optical model of the bolometer which includes all the layers that are present in the actual bolometer design. These are the bottom reflector, the Si/SiGe multi-layer thermistor, a silicon nitride (SiNx) layer functioning as the leg support material and a MoSi resistive top layer. To verify the model, we have manufactured test structures with this layer combination and determined the infrared absorption by evaluating the structures using a Nicolet Avatar FT-IR setup covering wavelengths between approximately 2.5 μm and 25 μm [6].

Figure 3 shows the measured absorption spectrum for a structure described above. The optical properties for MoSi, SiNx and SiGe were obtained using infrared ellipsometric measurements of the individual films, whereas the properties of pure Si were based on published data. The reflector is in this case assumed to be ideal.

Figure 3. Measured and simulated absorption spectrum for a bolometer structure consisting of a reflector, a Si/SiGe thermistor, a SiNx leg support layer and a MoSi film on the top surface.

The agreement between measurement and simulation is surprisingly good considering the simplicity of the model. The thickness of this particular sample was slightly too thin to provide optimal absorption in the long wave infrared range as is evident from the peak absorption position at a wavelength of approximately 7.6 μm. It is, however, quite straight forward to increase the thickness and thereby shift the absorption peak to longer wavelengths.

To further evaluate the optical model and material properties, a second test structure was manufactured without the SiNx layer present. This configuration represents a design where the legs are pushed to the limit of negligible thickness. For this configuration, the fit between the simple simulation and measurement is not as good as in the previous case (Figure 4).

Figure 4. Measured and simulated absorption spectra for a bolometer structure consisting of a reflector, a Si/SiGe thermistor layer and a MoSi layer on the top surface. The simulations cover the cases of perfect reflectance and finite reflectance.

With the simplified assumption that the bottom reflector is perfect, a significant discrepancy between simulation and measurement is observed. This was not the case for the bolometer structure that contained the SiNx leg material layer on top of the thermistor (Figure 3). To increase the accuracy of the model, the reflector material was independently characterized. Replacing the ideal reflector with the actual measured reflector improved the fit between simulation and measurement significantly (Figure 4). The twin peaks observed in the measurement were now also visible in the simulation and both the position of the peaks and their amplitude fit reasonably well. There is still a discrepancy between measurement and model for the longer wavelengths where absorption is higher in the measured data than in the simulation. Neither surface roughness, nor interfacial layers were considered in the model, and the inclusion of these could potentially improve the model fit.

3. HETEROGENEOUSLY INTEGRATED 17 MICROMETER PITCH BOLOMETERS

3.1 Bolometer design

As discussed previously, the bolometer presented is designed for applications in the 8-14 μm wavelength range. To support the description of the design, a detailed drawing of a bolometer pixel is shown in Figure 5.

Figure 5. Schematic drawing of a bolometer pixel. The most important materials are indicated.

The basic structure of the $17\mu\text{m} \times 17\mu\text{m}$ pitch bolometer pixel is a free hanging membrane suspended above the substrate by thin and narrow legs. The bolometer legs consist of a sandwich structure of SiNx, TiW and SiNx. The multi-layer leg design was chosen to manage mechanical stress and to encapsulate the thin TiW film that provides electrical contact between the substrate and the thermistor material. To achieve stress compensation of the legs, the lower SiNx layer is designed to be 150 nm thick while the upper SiNx layer is 200 nm thick. These two SiNx layers sandwich a 50 nm thick TiW layer. An etched trench through the uppermost highly doped silicon layer divides the top surface into two separate contact regions. As is shown in Figure 6, the electrical current flows vertically through the Si/SiGe quantum wells twice. Plated nickel pillars connect the legs to interconnect lines on the bottom substrate and allow the signal to be read out from the bolometers.

In the previous section, we described how the infrared absorption of the bolometer is optimized by designing the bolometer membrane as an optical $\lambda/4$ -cavity[14]. The optical cavity consists of a bottom aluminum mirror, followed by the epitaxially grown Si/SiGe thermistor, a SiNx passivation layer and a MoSi layer with approximately 377Ω sheet resistance as the uppermost layer.

The thermal conductance between the bolometer membrane and ambient should be as low as possible to maximize the bolometer sensitivity. However, care has to be taken to maintain a sufficiently small time constant to make the bolometer compatible with the image frame rate. The thermal response time of the bolometer is determined by the heat capacity of the membrane and the heat conductivity between the membrane and ambient according to Equation 2.

$$\tau = \frac{C}{G} \quad (2)$$

Here, τ is the thermal time constant, C the membrane heat capacity, and G the heat conductivity between the membrane and ambient. With a calculated heat capacity of approximately 2.9×10^{-10} J/K, the thermal conductance of the legs were chosen to obtain a thermal time constant of more than three milliseconds.

The bolometer fill factor is defined as the ratio between the actual bolometer area and the maximum possible pixel area given by the pixel pitch. The bolometer design in this study has fill factor of 68%.

Figure 6. Cross-section of a bolometer. The current path goes vertically through the epitaxially grown Si/SiGe quantum-well layers. The trench cuts the highly doped silicon between the upper contacts, which forces the applied current to travel through the quantum well structure.

3.2 Heterogeneous integration scheme for bolometer fabrication

The fabrication scheme for heterogeneous integration of the microbolometer arrays is shown in Figure 7. In the bolometer fabrication, the Si/SiGe quantum-well thermistor material is epitaxially grown on a 100 mm diameter silicon on insulator (SOI) wafer to a total thickness of 556 nm. A 50 nm thin aluminum layer is deposited on top of the SOI wafer to define the bolometer backside mirror. The SOI wafer with the epitaxially grown layer is then bonded to a 100 mm diameter fan-out wafer using non-aligned adhesive wafer bonding (Figure 7(a)). The fan-out wafer contains interconnect lines that can be used to electrically address individual bolometers in the arrays for characterization purposes. The fan-out wafer has a surface topography of about 500 nm which is similar to the topography of fully processed CMOS wafers. The fan-out wafer can be replaced by a CMOS read out IC wafer without modifying the integration process.

The handle substrate of the SOI wafer is removed using an SF_6 -based ICP etch process, stopping on the buried oxide layer. The buried oxide layer is then removed in buffered HF (Figure 7(b)). 30 nm of aluminum is sputter deposited and bolometer contact pads are defined on the transferred layer (Figure 7(c)). The transferred Si/SiGe quantum well layer is then masked and etched to define thermistor structures, which after this step consists of silicon mesas with aluminum contacts on top. This is followed by deposition of 150 nm PECVD SiN_x to cover both the bonding polymer and Si/SiGe mesas, which will become the thermistor elements of the bolometers.

Interconnecting via holes with a diameter of 3 μm are defined and etched through the SiN_x and the bonding polymer down to the metal lines on the fan-out wafer (Figure 7(d)). Nickel pillars are plated to fill the via holes using electroless plating (Figure 7(e)). 50 nm of TiW is deposited to electrically connect the thermistors and the plated nickel pillars (Figure 7(f)). The TiW metal is etched away from all areas of the wafer except where the legs will be defined. Another 200 nm thick PECVD SiN_x is deposited to achieve a triple stack sandwich leg structure of SiN_x , TiW and SiN_x that protects the thin metal lines and enables stress compensated straight bolometer legs. This is followed by deposition of a thin MoSi layer to enhance infrared absorption. The last masking and dry etching step defines the exact leg design and the bolometer membranes (Figure 7(h)). The bolometers are free-etched by removing the bonding polymer in an

isotropic oxygen plasma (Figure 7(i)). The final step is a forming gas anneal in Ar/H₂ for 30 minutes at 300 °C to decrease the contact resistances between the silicon and metal layers.

Bolometer arrays with a pitch of 17μm x 17μm and a leg width of 575 nm were successfully manufactured using the above described process. Images of the devices can be seen in Figure 8.

Figure 7. Integration scheme of important steps in the bolometer fabrication process. a) Wafer bonding of SOI wafer to a target wafer. b) Removal of silicon handle and buried oxide of the SOI wafer. c) Definition of aluminum upper contacts. d) Definition of Si/SiGe thermistors followed by PECVD SiNx deposition and etching of plating via holes. e) Plating of nickel pillars. f) Contacting nickel pillars and upper aluminum contacts with deposited TiW. g) Deposition of PECVD SiNx. h) Definition and etching of legs and bolometer membranes down to bonding polymer i) Release bolometer structures by etching away the bonding polymer with an isotropic oxygen plasma.

Figure 8. a) A 17μm x 17μm pitch bolometer. The legs are 575 nm wide and make electrical contact to the underlying substrate through plated nickel pillars. The membrane is suspended above the bottom substrate to increase the thermal isolation. b) Part of an array of 17 μm x 17μm bolometers.

3.3 Characterization of Si/SiGe bolometers

The TCR of the bolometers was determined by measuring the electrical resistance at different temperatures at atmospheric pressure. Biasing was made with 0.5 V square wave pulses. A measurement of the thermal conductance from the bolometers in atmospheric pressure was then used to adjust the temperature data for bolometer self heating due

to biasing. This resulted in adjustments of between 2-4 °C depending on the power dissipation at a specific temperature. The bolometer resistance was modeled using Equation 3, which works well when the parasitic series resistance of the legs is much smaller than the thermistor resistance. For the present case, the leg resistance was approximately 2 kΩ and the thermistor resistance close to 50 kΩ at room temperature supporting the use of this simple model.

$$R = R_{thermistor} \cdot e^{\left(\frac{\Delta E}{k_B} \left(\frac{1}{T} - \frac{1}{T_0}\right)\right)} \quad (3)$$

Here, k_B is the Boltzmann constant, T is the absolute temperature, T_0 a reference temperature at 298 K and ΔE is the quantum well barrier height. The resistance of the thermistor and the TCR at 25 °C were extracted from the data by fitting Equation 2 to the measured values (Figure 10). The TCR of the bolometers were determined to be -2.9 %/K. This fits well with earlier reported results for the Si/SiGe quantum well material[6].

Figure 10. Arrhenius plot of the resistance. A TCR value of -2.9%/K was extracted from the data.

Thermal conductance and heat capacity of the bolometer were measured in high vacuum where the leg thermal conductance dominates and evaluated by pulse biasing a Wheatstone bridge[15]. A typical response curve is shown in Figure 11. The thermal conductance was measured to be $G=6.9 \times 10^{-8}$ W/K and the heat capacity was $C=3.4 \times 10^{-10}$ J/K corresponding to a thermal time constant of $\tau = 4.9$ ms.

Some of the key characteristics of the bolometer design are summarized in Table 1. The numerical values agree well with theoretically calculated values.

Figure 11. The graph shows the bolometer response caused by self-heating when biased with a 400 mV square wave in a Wheatstone bridge configuration. The thermal conductance is extracted from the saturation voltage and the heat capacity is determined from the gradient of voltage response.

Table 1. Summary of key bolometer characteristics determined by measurements.

Bolometer characteristics	Value	Unit
Resistance at 25 °C	59	kΩ
Fill factor	68.3	%
C	3.4×10^{-10}	J/K
G	6.9×10^{-8}	W/K
τ	4.9	ms
TCR	- 2.9	%/K

4. DISCUSSION

The calculated infrared absorption spectrum agrees well with measurements done on a test structure for the case where the SiN_x leg material is present as part of the optical quarter wave cavity. For the degenerate case where the SiN_x is completely removed, the simulation qualitatively agrees with measurements, but there are differences that need further investigation. Neither surface roughness, nor the presence of interfacial layers is present in the current model. The fact that a significant discrepancy between model and measurement is only observed for the case of a thin structure supports the suggestion that one of these phenomena could be responsible for the lack of fit. Despite the issues of less than perfect fit of model to measurement for one of the investigated cases, the overall infrared absorption of the bolometer is encouragingly high reaching peak values above 95% in both cases.

The manufactured bolometers were evaluated both electrically and thermally and excellent agreement between expected characteristics and measurements were observed. The TCR value of -2.9%/K is fully in line with expectations for a Si/SiGe thermistor structure with approximately 30% Ge fraction[6]. The calculated heat capacity of $C_{\text{expected}}=2.9 \times 10^{-10}$ J/K is very close to the measured value of $C=3.4 \times 10^{-10}$. With a measured thermal time constant of $\tau=4.9$ ms, it is also shown that bolometers manufactured using heterogeneous integration are suitable for imaging systems with a frame rate of 60 Hz. Tuning the design and manufacturing process of the legs is quite straight forward,

allowing further increase of the thermal time constant which will be beneficial for the bolometer sensitivity while still allowing high frame rate operation.

5. CONCLUSIONS

Successful manufacture of $17\mu\text{m} \times 17\mu\text{m}$ bolometers was accomplished using a heterogeneous integration process where the Si/SiGe sensor material is transferred to a fan-out board wafer by adhesive wafer bonding. The bolometer manufacturing employs standard MEMS technologies allowing implementation at foundries with relative ease. Electrical and thermal characterization show that the integration process results in pixels with characteristics very close to the expected.

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