Fulfilling the pedestrian protection directive using a long-wavelength infrared camera designed to meet both performance and cost targets

Jan-Erik Källhammer * [a], Håkan Pettersson [a], Dick Eriksson [a], Stéphane Junique [b], Susan Savage [b], Christian Vieider [b], Jan Y. Andersson [b], John Franks [c], Jan Van Nylen [c], Hans Vercammen [c], Terje Kvisterøy [d], Frank Niklaus [e], Göran Stemme [e]

[a]Autoliv Research, 447 83 Vårgårda, Sweden
[b]Acreo AB, Electrum 236, 164 40 Kista, Sweden
[c]Umicore Electro-Optic Materials, Watertorenstraat 33, 2250 Olen, Belgium
[d]Infineon Technologies SensoNor AS, P.O.Box 196, N-3192 Horten, Norway
[e]Royal Institute of Technology, 100 44 Stockholm, Sweden

ABSTRACT

Pedestrian fatalities are around 15% of the traffic fatalities in Europe. A proposed EU regulation requires the automotive industry to develop technologies that will substantially decrease the risk for Vulnerable Road Users when hit by a vehicle. Automatic Brake Assist systems, activated by a suitable sensor, will reduce the speed of the vehicle before the impact, independent of any driver interaction. Long Wavelength Infrared technology is an ideal candidate for such sensors, but requires a significant cost reduction. The target necessary for automotive serial applications are well below the cost of systems available today. Uncooled bolometer arrays are the most mature technology for Long Wave Infrared with low-cost potential. Analyses show that sensor size and production yield along with vacuum packaging and the optical components are the main cost drivers. A project has been started to design a new Long Wave Infrared system with a ten times cost reduction potential, optimized for the pedestrian protection requirement. It will take advantage of the progress in Micro Electro-Mechanical Systems and Long Wave Infrared optics to keep the cost down. Deployable and pre-impact braking systems can become effective alternatives to passive impact protection systems solutions fulfilling the EU pedestrian protection regulation. Low-cost Long Wave Infrared sensors will be an important enabler to make such systems cost competitive, allowing high market penetration.

Keywords: infrared bolometer, infrared imaging, automotive safety, pedestrian injury mitigation systems, Brake Assist system, GASIR, low-cost optics, MEMS, SiGe, quantum-well structure.

1. INTRODUCTION

Pedestrian fatalities are around 24% of all traffic fatalities worldwide[1] and about 15% of the traffic fatalities in Europe[2]. The European Commission is aiming at decreasing fatalities in traffic and specifically improving safety of pedestrian and other Vulnerable Road Users (VRU). This is reflected by an EU Regulation that requires the automotive industry to develop technologies that will substantially decrease the risk for a pedestrian or cyclist to be killed or seriously injured when hit by a car. A new draft proposal for the regulation was issued in 2005, which can be summarized as follows[3] :

(a) a first phase set of test requirements (phase I) will apply to all new types of vehicles as from 1 October 2005 and to all new vehicles placed on the market after 31 December 2012;

(b) a second phase set of tests (phase II), based on the results of the comprehensive study carried out into the feasibility of the original requirements, will apply to all new types of vehicles from 1 September 2010 and to all new vehicles by 2015;

* jan-erik.kallhammer@autoliv.com

(c) the active safety system, Brake Assist, will be required in all new vehicles as from 1 July 2008;
(d) the use of new systems, such as collision avoidance, will be recognised as alternatives;
(e) the repeal of Directive 2003/102/EC.

Of main interest for this paper is item (d), although item (c) is an important enabler: Brake Assist is a system that reduces the braking distances by applying full braking power in situations identified as a panic stop. This is done by monitoring the rate of brake application[4]. The stopping distance is reduced due to the fact that drivers often do not apply the brakes fast and hard enough to minimize the actual stopping distance. The current functionality of Brake Assist system has been estimated to greatly reduce the pedestrian fatality rate according to a study by Transport Research Laboratory (TRL) under contract by the European Commission[5]. The TRL study showed that when comparing the current phase 2 of the Pedestrian Protection Directive with the effects of a regulation with mandatory Brake Assist systems, as proposed by the European Automobile Manufacturers Association (ACEA), an additional 16% pedestrian fatalities would be saved. A Brake Assist system is, however, dependent on a rapid reaction by the driver. The availability of Brake Assist systems in all cars means that an actuator will be available that can be used to also autonomously apply the system when complemented with a suitable sensor. Such a system is expected to comply with alternative (d) above in the draft EU proposal.

An automatic Brake Assist system can reduce the speed of the car before an impending pedestrian impact independent of any driver interaction. A system that automatically brakes the vehicle when a risk of impact is detected, will significantly reduce the fatalities and level of injuries. For a car traveling at 50 km/h it takes 0,72 s to move 10 m. Activating the brakes with a mean level of 0.6 g when the car is 10 m before the impact with the pedestrian reduces the impact velocity to 31 km/h. Accident data from the International Harmonization Research Activity (IHRA) [5], indicate that this would reduce the risk of fatality from about 35% to about 10 %, which can be seen in Figure 1. The driver either does not react at all, or does not apply the brakes with sufficient rate to activate the Brake Assist system in 53% of the pedestrian accidents according to a study of the University of Dresden[6]. This implies that the fatality reduction potential with an autonomously activated Brake Assist system would be up to double the estimated 16% fatality reduction possibility of current Brake Assist systems. There are at least two advantages of pre-impact braking: The impact energy will be reduced significantly and the common secondary impact when the pedestrian hit the street will also be reduced. The less severe injuries are in fact more frequently caused by the secondary impact[1]. Pre-impact braking is the only protection method for pedestrians to reduce the second impact[7].

Necessary for a realistic realization of an autonomous pedestrian protection Brake Assist system is of course the availability of a robust and cost effective sensor system that can be afforded as serially installed equipment. The fact that collision avoidance systems will be recognized as alternative means of fulfilling the regulation will likely generate a powerful incentive to look into various systems that prevent, or mitigate, the consequences of pedestrian and other Vulnerable Road Users accidents by taking action before the actual impact takes place. Additional benefits besides pre-impact braking could come from reversible, deployable protection system in the front and bonnet regions of the vehicle that would allow additional reductions of fatalities and injuries of children and adult pedestrians.

Although we are currently dealing with a regulation proposal, it appears likely that a final ruling will resemble the current draft. The last implementation dates may be modified and specification and verification criteria of system according to item d are expected.

Collision mitigation by means of autonomous braking is also addressed in the COMPOSE sub project within the PReVENT integrated project. This sub project develops and evaluates collision mitigation and Vulnerable Road User protection systems for trucks and cars[8].

Long-Wavelength Infrared (LWIR) thermal cameras are particularly well suited to detect human beings and animals, who present a high signal to noise ratio versus ambient due to their higher temperature. These cameras should make the picture less difficult to interpret for an automatic vision algorithm. An appreciable advantage of LWIR systems is that they do not need an external illumination source. The LWIR systems are also immune to the blinding effects by other illumination sources such as the headlights of oncoming cars. However, the high cost of today's systems has restricted the use of LWIR[9]. Applications of LWIR technology into a high volume automotive application require a significant cost reduction effort. However, there are no off-the-shelf LWIR cameras available today that are compatible with such applications in terms of performance and costs. The proposed revised EU directive may generate the required high-volume application that will justify the development of application-specific low-cost LWIR cameras.

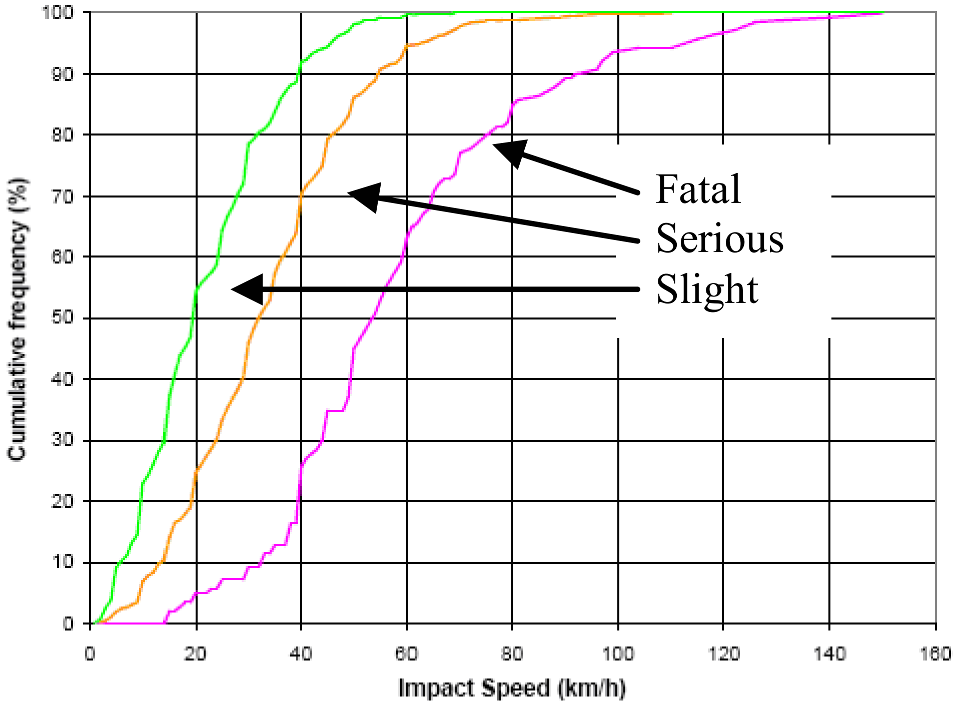

Figure 1: Pedestrian fatality and injury risks as a function of impact speed[5].

To address this issue, a project has been started to design from the ground up a new low-cost LWIR camera, with a ten times cost reduction potential. A LWIR sensor optimized for the low cost, high-volume, short range requirements necessary for an automotive pedestrian detection application can take advantage of the recent progress in Micro Electro-Mechanical Systems (MEMS) sensor development[10-12] and some of the inherent restrictions in the application. The project is called Pedestrian Injury Mitigation Systems (PIMS), focusing on detection of pedestrians in front of the car and forecasting an unavoidable collision. The project is based on a concept study funded under the Swedish Intelligent Vehicle Safety Systems initiative[13] that formed the basis for a continued project now underway under the Eurimus/EUREKA program[14]. The outcome of the project is also expected to benefit other LWIR application areas.

The PIMS project will end during the second quarter of 2008, and the timing target for the final product aims to fulfill at least the latter proposed regulation described in item b) above i.e. by 2015 for all new vehicles.

The remainder of this paper will cover the initial specifications and then proceed with the approach to tackle the main cost drivers of today's LWIR systems; the detector, its packaging and the LWIR optical system.

2 SYSTEM SPECIFICATION

The initial cost analysis shows that sensor size (resolution) and production yield are the two main factors affecting the cost of the sensor. Higher resolution will negatively affect the yield. For a low cost sensor there are therefore important incentives to limit the resolution. System performance in terms of detection distance and covered area - Field of View

(FoV), both drive the required resolution: The further away detection has to be made for a given covered area, the higher resolution is required. Similarly, for a larger covered area, a higher resolution is needed for a given detection distance. The system requirements therefore have to be carefully examined in order to avoid over-specification that will drive the system cost up. Increased resolution will also have a direct effect on the required processing power[7].

The detection distance is governed by the protection level required, expressed in terms of speed reduction capability. A higher average braking level would allow the same injury mitigation level to be achieved with brake-activation closer to the impact. Disadvantages of higher braking levels include potentially higher risks of rear-impact collisions, while lower braking levels means that the system must detect the object further away from the vehicle. The further away a pedestrian is located from the vehicle, the greater the chance is that the driver or the pedestrian by his own measures will avoid the accident. Autonomous activation of the braking system when the driver by himself already is engaged in maneuvers to avoid an accident or an incident could be considered as an inadvertent activation. The acceptance of such activations by the driver is expected to be limited and must be kept low[7].

The required covered sensed area or Field of View is another parameter which will drive cost and is governed by the speed at which a pedestrian, bicyclist, or other Vulnerable Road User will enter from the side into the path of the vehicle. Especially pedestrians coming out from a blocked view, e.g. entering the street from behind a parked vehicle, will determine the required Field of View of the system.

The detection distance coupled with the required Field of View determines the sensor resolution. Higher resolution will increase the sensor size and negatively affect the yield.

The LWIR systems available in cars today all have either shutters or choppers. Besides adding cost and package envelope, shutter operation would also have to be scheduled not to interrupt signal acquisition in critical situations. Shutter-less operation is therefore an important design objective. The fact that no image is required to be displayed to the operator and application constraints, will simplify a shutter-less design.

System specification will be enabled as well by selecting the right LWIR lens material. Both germanium and GASIR® based designs exhibit very specific properties in terms of MTF and F-numbers as related to manufacturing yield and tolerances.

Based on the above considerations, a preliminary specification was established, see Table 1:

Table 1: Preliminary specification.

Noise equivalent temperature difference (NETD) with F=1	**150mK**
Frame rate	**25 Hz**
Pixel size	**25 – 35 μm**
Number of pixels	**80 x 30**
F-number	**F < 1**
Field of View (FoV)	**55 degrees**
Operation/detection distance	**10 m**
Optics focal length	**2 – 3 mm**
Cost target for total sensing system	**< € 100**

The outcome of the project will be a prototype system used to evaluate the key components developed. The results of the evaluation will drive the final specification of the production intent system. Therefore, the final specification may change during the course of the project. The current specification may therefore only have to be accurate enough to warrant concept evaluation of the key components in a range reasonable for the intended product. The system is schematically shown in Figure 2.

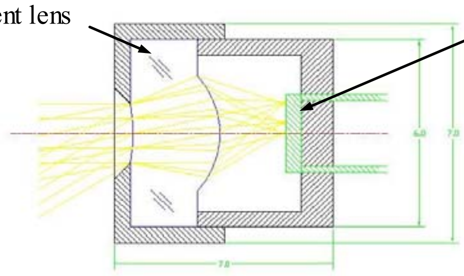

Figure 2: Schematic cross-sectional view of the key parts of the infrared imaging component.

3 LONG-WAVELENGTH INFRARED IMAGING ARRAYS

To reach the cost target for pedestrian injury mitigation systems in automotives, the cost of the infrared imaging chips need to be well below the cost of those commercially available today. Uncooled infrared bolometer arrays utilize the most mature and established low-cost technologies for long-wavelength infrared imaging The main features of uncooled infrared bolometer arrays that contribute to their low cost potential are that they do not necessarily require a chopper, chip temperature stabilization or chip cooling and they can be manufactured using Micro Electro-Mechanical Systems (MEMS) and integrated circuit (IC) technologies.

A novel 3D integration technique has been developed for the manufacturing of infrared bolometers on top of complementary metal oxide semiconductor (CMOS) based read-out-integrated circuits (ROICs)[10-12]. The manufacturing process of the 3D integration technique is depicted in Figure 3. The bolometer materials are deposited and optimized on a wafer separately from the ROIC wafer, which allows using high-temperature fabrication processes on the bolometer wafer. This allows the use of high-performance temperature sensing bolometer materials such as e.g. epitaxially grown crystalline Si/SiGe multi-layer structures (quantum well structures). In these structures, Si is used as a barrier and SiGe as the well material as indicated in Figure 4. By optimizing parameters such as the barrier height V_0 (by variation of the germanium content) and the fermi level E_f (by variation of the quantum well width and doping level) these materials provide the potential to engineer layer structures with a very high temperature coefficient of resistance (TCR). Simultaneously, the high quality crystalline material promises very low 1/f-noise characteristics and well defined and uniform material properties. The high performance temperature sensing material is transferred from the original substrate wafer (handle wafer) to the ROIC wafer using adhesive wafer bonding as shown in Figure 3. This 3D bolometer integration technique is compatible with standard CMOS wafers and MEMS foundry processes and uses standard semiconductor materials in the bolometer construction. This is in contrast to conventional monolithic bolometer manufacturing approaches, in which often customized deposition processes and materials are used (e.g. vanadium oxide, VO_x and amorphous silicon, α-Si)[15,16].

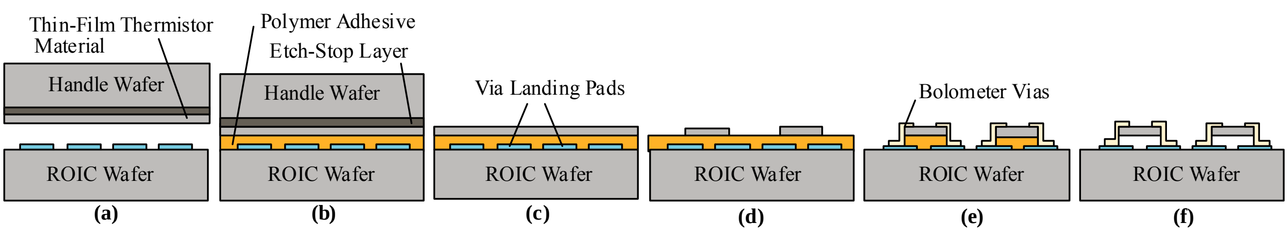

Figure 3: 3D integration for uncooled infrared bolometer arrays: (a) fabrication of ROIC wafer and separate handle wafer with thermistor material (b) adhesive wafer bonding (c) thinning of handle wafer (d) bolometer definition (e) via formation (f) sacrificial etching of adhesive.

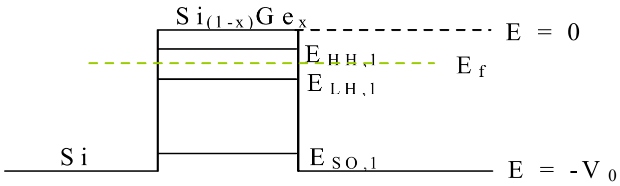

Figure 4: Valence band structure of SiGe.

A detailed cost analysis for the manufacturing and packaging of infrared imaging chips has shown that the chip size, the manufacturing yield and the vacuum packaging technique have the largest impact on the final chip cost. Small infrared imaging chip areas can be achieved by small array formats and small bolometer pixel pitches. This results in a larger number of chips per wafer and increased manufacturing yield and hence reduced costs. In addition, decreased vacuum levels in the chip package can lead to reduced costs. However, calculational models for the system sensitivity or noise equivalent temperature difference (NETD) show that the bolometer pixel size and a high gas pressure in the chip package (resulting in an increased thermal conductance between the bolometer and its surroundings[17]) increases the NETD of the infrared imaging arrays (= decreases the system sensitivity)[9,16,18,19]. Thus, a trade-off between cost and performance has to be made.

The noise equivalent temperature difference (NETD) of an infrared sensing system is defined as the difference in temperature between two side-by-side blackbodies of large lateral extent which, when viewed by the infrared sensing system, gives rise to a difference in signal-to-noise-ratio of 1 in the electrical outputs of the two halves of the sensor array. For a pedestrian injury mitigation system in the application described, the required NETD is estimated to be on the order of 150 mK and the required pixel count is on the order of 80 x 30 pixels. The use of high-performance, mono-crystalline bolometer materials with a TCR of 2 to 3 %/K and a low 1/f-noise leads to a significant reduction in the NETD as compared to more commonly-used bolometer materials such as VO_x and α-Si bolometers[16]. Our calculations indicate that the bolometer pixel size can be decreased to 25 µm x 25 µm and the gas pressure in the vacuum package increased to about 10 mbar, while still maintaining a NETD on the order of 150 mK. These requirements on the vacuum package gas pressure are within the range of cost-efficient wafer-level vacuum packaging techniques. In addition, the long-term stability requirements of the vacuum packages are easier to meet if the minimum required gas pressures are relatively high.

4 LOW-COST PACKAGING

MEMS products like automotive inertia and pressure sensors[20] have during the past 10 years clearly shown the benefits of MEMS miniature packaging in relation to manufacturing cost and long term reliability of pressure control and contamination control for hermetically sealed cavities[21]. The next generation “3D Heterogeneous Microsystems” technology will strengthen the benefits using chip and wafer stacking and in the long run outperform the traditional packaging of sensors and micro systems. By adaptation of already available MEMS wafer bonding technology[22], a wafer scale package containing the bolometer pixel array in a hermetic cavity and the electrical wire bond pads outside the cavity will be created, as illustrated in Figure 5. This will secure a constant gas environment for the life time of the product. In addition to securing the stable gas environment and creating good mechanical protection, the enclosure must allow the IR radiation to reach the bolometer pixels. In general the manufacturing process is appropriate for both silicon and germanium window materials, but the manufacturing yield is believed strongly to relate to the maturity of already established processes. For both materials a special process for “selective” deposition of conformal antireflection coating into the deep open recesses need to be established, as depicted in Figure 5. The 3D integration process will be developed using exclusively CMOS compatible processes, like Chemical Mechanical Polishing to prepare the ROIC wafer bonding surface, and MEMS processes that are available in commercial foundries, like Anodic Bonding or metal-to-metal thin film Direct Wafer Bonding. For the cavity gas pressure, two strategies seems complimentary dependant upon the overall system targets. First low pressure, $<10^{-3}$ mbar will require thin film getter material to be deposited on the surfaces inside the cavity. Second, medium pressure, <1 mbar, is close to available "getter free" industry processes. In the case of using thin film getters[23], much emphasizes will be put into design of the activation method. Already established manufacturing schemes using accelerated testing for checking the actual gas pressure and bonding consistency, must be adapted for IR characteristics.

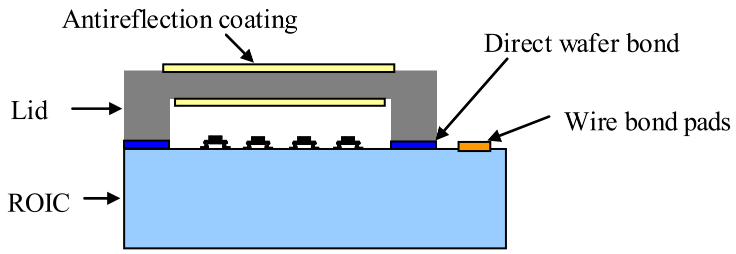

Figure 5: Schematic Bolometer "miniature packaging".

5 OPTICAL DESIGN

To keep the camera cost as low as possible, we decided to concentrate on single-lens solutions. Germanium and Umicore's GASIR® were investigated as lens materials. Germanium is a high performance material for long-wavelength infrared lenses, with a high mechanical resistance and a refractive index of 4.0. Germanium is however an expensive material and single point diamond turning is the only way to produce aspheric surfaces. Single point diamond turning is an expensive process and is difficult to use in a cost-sensitive, volume production. GASIR® is an infrared-transmitting glass with a refractive index of 2.5. It is an attractive candidate for high-volume infrared lenses as it can be molded into a finished lens. In addition, GASIR® is less dependant on the germanium market price, since it is a chalcogenide glass containing less than one third germanium.

To evaluate the feasibility of single-lens designs, optical designs were optimized for sensors with 80x30 to 160x60 pixels, pixel pitches of 20µm to 40µm, and for camera field-of-view of 45° to 70°. The sensors are placed behind a silicon or germanium window, and mounted in a single-lens optical system, as illustrated in Figure 6. The system aperture was placed in front of the entry surface of the lens. For each design, the lens was optimized to provide the highest MTF at the maximum spatial frequency f_{max} detectable by the infrared sensor. The aperture was then increased, and the lens re-optimized, until the MTF at f_{max} decreased to 0.3. This state was considered the optimal optical design for a given configuration. It provides the maximum optical throughput (and hence the best NETD for a given sensor) while maintaining the minimum requested imaging performance.

Aspheric, spherical and flat surfaces were tested for both germanium and GASIR® lenses, as were sensor windows in silicon and germanium. F-numbers of the obtained optical systems were compared.

For aspheric lenses we observed that germanium and GASIR® are two good candidates as lens materials for infrared cameras. The F-numbers achieved for germanium and GASIR® were in the range 0.7 to 1.4. The performance was broadly similar for the two materials however, in general, there was a small improvement (decrease) of the F-number of germanium over GASIR®.

However when cost considerations were included a different result became apparent. Since for molded GASIR® optics the cost of aspheric surfaces is broadly similar to the cost for spherical surfaces, aspheric GASIR® lenses can be compared with spherical germanium lenses. In this case GASIR® is a much better solution since the F-number given by spherical germanium ranged from 1.5 to 3.0. The lowest cost solution are plano-convex GASIR®

lenses. In this case, however, the maximum F-number is reduced to a level much below that of other lens designs. A cost–benefit analysis will be necessary to determine which of the GASIR® solutions are most appropriate.

Both germanium and silicon are candidates for the window material of the infrared sensor and the choice of material has a negligible impact upon the MTF of the system. However, the absorption in a silicon window is higher with the total absorption directly related to the window thickness.

A tolerance study has shown that germanium and GASIR® lenses have similar fabrication requirements. The second lens surface is much more sensitive to manufacturing tolerances than the first one (0.1% compared to 1-5%). The positioning accuracy of the lens is critical and needs to be within 10µm of the nominal position. The requirement for positional, flatness and thickness tolerances on the detector window are easily met by the current manufacturing technology and so will not be a cost driver in the manufacturing process.

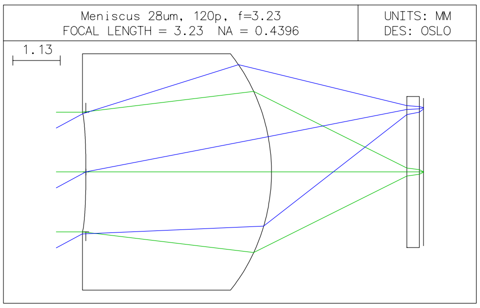

Figure 6: 2D view of a single-lens optical design including an aspheric meniscus lens in GASIR® material (left) and an infrared sensor behind its silicon or germanium window.

6 LOW-COST IR OPTICS MANUFACTURING STRATEGY

Traditionally LWIR systems use germanium optics, which are relatively expensive and prohibit a smooth transition to affordable high-volume systems. GASIR® has been introduced to overcome this. It has the advantage of a very low content of germanium, the most expensive of its constituents. This results in a less expensive starting material. More importantly, the major improvement of GASIR® optics compared to germanium or other traditional materials is the fact that GASIR® can be molded with good quality into complex shapes without expensive processes such as diamond turning or polishing. Spherical, aspherical and asphero-diffractive shapes can be molded without the need for further post-processing steps.

A drawback of chalcogenide glasses compared to germanium is the higher chromatic dispersion. For this reason, optics using infrared glass need to be achromatized using diffractive or binary surfaces. Prior to the development of molding, these had to be manufactured using single point diamond turning which is a costly process. This led to a low demand for this type of material and its use limited to complex systems where the performance benefits outweighed the cost implications. However by using molding, diffractive patterns can be manufactured at no additional cost to the consumer. The accuracy of molding these diffractive patterns is comparable to single point diamond turning and the step height regularity is better than 0.2 µm. Therefore molding of complex surfaces in GASIR® now yields surface accuracy and unit costs sufficient to make it attractive for both high and low performance, high volume optical systems.

In this work, both germanium and GASIR® based design solution will be evaluated.

In a first phase the optimal manufacturing solution will be assessed. The established flow sheet of GASIR® molding[24-26] will be compared with novel germanium finished optics manufacturing technologies. Production of a low-cost high-volume single optical element with a diameter of less than 10 mm will be essential

The optical system specifications will be balanced. Individual component specifications like refractive optics, detector, software, and packaging will be combined. This will lead to the design of a production flow sheet exactly tuned to the application specifications. This differs from military approaches were no compromises are made on high-resolution, high-quality optical performance. A critical requirement for a forward facing optical element in a car is the development of a coating with appropriate anti-reflective and anti-erosion properties. Traditionally DLC coatings are used for this purpose. DLC coating on GASIR® will be developed.

Finally prototype germanium and GASIR® based optics will be manufactured and evaluated together with the other system components.

7 CONCLUSION

It is estimated that deployable systems and automatic braking systems can become an effective alternative to fulfilling the EU pedestrian protection directive. The proposed low-cost Long Wave Infrared (LWIR) sensor is expected to become an important enabler and allow this type of systems to be cost competitive and to allow high market penetration.

There will always be different solutions in a competitive market, but the aim of the approach taken in this proposal is to take a significant share of the market. As the European Automotive market alone is in the range of 17 million new vehicles per year, the potential market for a low cost Pedestrian Protection system is many millions units annually. A single-lens uncooled LWIR camera system is therefore an attractive solution for pedestrian protection applications. However, there are still technical challenges to be solved

The proposal will pull together and further develop advances in optics and detectors. The development of the optical subsystem will advance cutting edge technology in materials, manufacturing processes and durable coatings. 3D heterogeneous integration will be used for the infrared bolometer fabrication, allowing high-performance crystalline sensing materials to be integrated on top of read-out electronic circuits. The bolometer fabrication uses only standard semiconductor materials and can be done in existing MEMS foundries. A bolometer wafer scale miniature package containing the bolometer pixel array in a hermetic cavity implemented in a standard MEMS foundry process, has been proposed. For systems requiring the best NETD, the proposed solution is compatible with use of thin film getters inside the hermetic wafer level cavity. Similar solutions used for automotive inertia and pressure sensors have demonstrated enhanced life-time reliability.

8 ACKNOWLEDGEMENTS

The authors would like to thank the Eurimus/EUREKA organization for supporting the PIMS project. The Swedish participants would like to thank VINNOVA (the Swedish Governmental Agency for Innovative Systems) for the support and the IVSS-program (Intelligent Vehicle Safety Systems) for the funding of the preceding Swedish PIMS project Finally Umicore would like to acknowledge pending support from the IWT (Institute for the Promotion of Innovation by Science and Technology in Flanders.).

REFERENCES

1. SAVE-U EU Project Deliverable 1-A, "Vulnerable Road User Scenario Analysis", http://www.save-u.org/download/PDF/D1A_V4.pdf, downloaded 15 Feb. 2006.
2. D. M. Gavrila, "Sensor-based Pedestrian Protection", IEEE Intelligent Systems, Vol. **16**(6), pp.77-81, 2001.
3. "Preliminary draft proposal for a regulation on the protection of pedestrians and other vulnerable road users before and in the event of a collision with a motor vehicle and amending Council Directive 70/156/EEC", http://europa.eu.int/comm/enterprise/automotive/pagesbackground/pedestrianprotection/consultation_phase_II/preliminary_draft_proposal.pdf, downloaded 15 Feb 2006.
4. Continental Teves, http://www.conti-online.com/generator/www/us/en/continentalteves/continentalteves/themes/products/brake_actuation_folder/brake_assist_en.html, downloaded 15 Feb 2006.
5. G. J. L. Lawrence, B. J. Hardy, J. A. Carroll, W. M. S. Donaldson, C. Visvikis, and D. A. Peel, "A study on the feasibility of measures relating to the protection of pedestrians and other vulnerable road users - Final report", http://europa.eu.int/comm/enterprise/automotive/pagesbackground/pedestrianprotection/pedestrian_protection_study.pdf, EU Contract no FIF. 20030937 , downloaded 15 Feb 2006.
6. Hannawald L., Krauer F., "Equal effectiveness study on pedestrian protection", Dresden, Germany: Technische Universität Dresden, http://europa.eu.int/comm/enterprise/automotive/pagesbackground/pedestrianprotection/summary_on_effectiveness.pdf, downloaded 15 Feb 2006.
7. Meinecke M.M, Obojski M.A., Gavrila, D., Marc E., Morris R., Töns M., Letellier L. "Deliverable D6: Strategies in Terms of Vulnerable Road User Protection" http://www.save-u.org/download/PDF/D6_V3.0.pdf, downloaded 15 Feb 2006.
8. The COMPOSE sub project within the PReVENT integrated project, http://prevent-ip.org/en/prevent_subprojects/vulnerable_road_users_collision_mitigation/compose/, downloaded 15 Feb 2006.
9. J.J. Yon, L. Biancardini, J.L. Tissot, L. Letellier, "Infrared microbolometer sensors and their application in automotive safety", *Proc. AMAA 2003*, pp.1-15, Berlin, Germany, http://www.save-u.org/download/PDF/AMAA_200305.pdf, 2003, downloaded 15 Feb 2006.
10. F. Niklaus, J. Pejnefors, M. Dainese, M. Haggblad, P.-E. Hellström, U.J. Wallgren, G. Stemme, "Characterization of transfer-bonded silicon bolometer arrays", Proc. SPIE, Vol. 5406, pp. 521-530, Orlando, USA, 2004.
11. F. Niklaus, E. Kälvesten, G. Stemme, "Wafer-level membrane transfer bonding of polycrystalline silicon bolometers for use in infrared focal plane arrays", Journal of Micromechanics and Microengineering, Vol. **11**, pp. 509-513, 2001.
12. F. Niklaus, G. Stemme, J.-Q. Lu, R.J. Gutmann, "Adhesive wafer bonding", Journal of Applied Physics: Applied Physics Reviews, Vol. **99**, pp.031101-031128, 2006.
13. Invest In Sweden Agency, "IVSS: Intelligent Vehicle Safety Systems", http://www.isa.se/upload/english/Publications/IVSS.pdf, , downloaded 15 Feb 2006.
14. The Eurimus/EUREKA web site, http://www.eurimus.com/index.php?flashOK=10
15. C. Jansson, U. Ringh, K. Liddiard, N. Robinson, "FOA/DSTO uncooled IRFPA development", Proc. SPIE, Vol. 3698, pp. 264-275, Orlando, USA, 1999.
16. P.W. Kruse, "Can the 300 K radiating background noise limit be attained by uncooled thermal imagers ?", Proc. SPIE, Vol. 5406, pp.437-446, Orlando, USA, 2004.
17. P. Eriksson, J.Y. Andersson, G. Stemme, "Thermal characterization of surface-micromachined silicon nitride membranes for thermal infrared detectors", IEEE Journal of Microelectromechanical Systems, Vol. **6**(1), pp. 55-61, 1997.
18. P.L. Marasco, E.L. Dereniak, "Uncooled infrared sensor performance", Proc. SPIE, Vol. 2020, pp. 363-378, San Diego, USA, 1993.
19. V.Y. Zerov, V.G. Malyarov, I.A. Khrebtov, "Calculational modeling of the main characteristics of an uncooled linear microbolometer array", Journal of Optical Technology, Vol. **7**(3), pp. 153-157, 2004.
20. R. Grelland, "Tyre Pressure Monitoring Microsystems", Advanced Microsystems for Automotive Applications 2001, Springer Verlag, p245-251, 2001.
21. Henrik Jakobsen, "Absolute Pressure Sensors – Low Cost and High Reliability", Micro Structure Bulletin, Vol. **7**(1), Feb. 1999.

22. Infineon Technologies SensoNor AS, MEMS Foundry Process: www.multimems.com, as of the 15 Feb 2006.
23. The SAES Getters Group, “MEMS go getters”, www.eurosemi.eu.com, July 2005.
24. X. H. Zhang, Y. Guimond and Y. Bellec "Production of complex chalcogenide glass optics by molding for thermal imaging", Journal of Non-Crystalline Solids, Volumes 326-327, pp 519-523, 1 Oct. 2003.
25. Y. Guimond, J. Franks, Y. Bellec and A. Bourget “Umicore opens new era in IR moulded optics by opening the first high volume facility”, *Defence and Security Symposium*, proc. SPIE, Vol 5783, Orlando, USA, march 2005.
26. Y. Guimond, J. Franks and Y. Bellec, “Comparison of performances between GASIR moulded optics and existing IR optics”, *Defence and Security Symposium*, proc. SPIE, Vol. 5406, Orlando, USA, April 2004.