

Uncooled Avalanche Photodiode Arrays for the SWIR Using SiGe Technology

M.J. Palmer, R.E. Godfrey, D.J. Fulgoni, L.J. Nash, A.D. Capewell, C. Meaton, D.L. Pratt.
AdvanceSis Ltd, Barclays Venture Centre,
Sir William Lyons Road, Coventry, CV4 7EZ, UK.

A.P. Morrison
Department of Electrical and Electronic Engineering
University College Cork, Ireland.

Abstract

We investigate the feasibility of the use of substrates consisting of germanium on a silicon platform to create Avalanche Photodiode (APD) detectors for short wavelength infrared radiation. The proposed solutions have the benefits of combining the excellent electronic properties of silicon, particularly in respect to the avalanche multiplication process, with the optical properties of germanium for detection at 1.55 μm . Some experimental work has been performed in assessing the growth techniques in Chemical Vapour Deposition (CVD) required to produce high quality substrates and to form the required detector device structures.

Keywords: SWIR, Infrared, APD, Avalanche, Ge, Si, Geiger-Mode

Introduction

Short Wave Infrared (SWIR) detectors have found use in areas such as 3D Active Imaging, Lidar, fibre optic communications, biomedical spectroscopy and other imaging applications. Operation at wavelengths around 1.55 μm is eye-safe allowing more powerful laser systems to be used for imaging and communications. Working at this wavelength allows imaging through fog or smoke or other media that scatter visible light.

Silicon photodetectors are common for optical wavelengths. Silicon is used because of its good electrical properties and the ease by which it can be processed to form detector and electrical device structures. These same reasons have meant that it dominates the semiconductor electronics market. This fact adds to the case for using silicon as a detector since the existing semiconductor industry infrastructure can

be used, reducing cost, time to market and required investment in manufacturing facilities. For the avalanche multiplication process, silicon is the most appropriate choice for the detector material since there is a distinct asymmetry in the ionisation coefficients for electrons and holes, where the ionisation process is dominated by electrons leading to avalanche photodiodes with the lowest possible excess noise factor [1].

The main disadvantage with silicon is the high electronic bandgap (1.12 eV) leading to poor absorption in this material over the entire wavelength range of interest. Silicon is only useful as an absorber for wavelengths up to approximately 0.9 μm . For imaging and ranging applications in the short-wave infra-red (SWIR), typically in the wavelength range 0.8 μm to 1.6 μm the required materials must have bandgap energies in the range 1.55 eV to 0.78 eV. Suitable candidates are Ge, SiGe alloys and

III-V compounds based on InP such as InGaAsP and InGaAs. Figure 1 shows the absorption capabilities of several of these.

SWIR APD detectors have been demonstrated using alloys of group III and group V elements such as InGaAs. However these suffer from incompatibility with silicon and therefore cannot make use of the silicon semiconductor industry infrastructure. Also their excess noise factors are worse than those of silicon due to similar ionisation coefficients for holes and electrons.

Germanium is a promising candidate material, due to its narrow bandgap energy and the potential for integration with silicon substrates by one of several mechanisms. However, to form the entire detector in germanium will lose the advantages of silicon already outlined above. Also, the smaller bandgap of germanium may mean it is unable to sustain the high voltages required in APD devices without suffering from excessive leakage. Therefore it is proposed to form the multiplication region in silicon.

Although more compatible with silicon than III-V compounds, there are issues with integrating germanium with silicon. In particular, the larger atomic repeat distance of germanium tends to generate dislocations which act as generation-recombination centres, increasing dark current and reducing efficiency. Therefore the techniques used to form the Ge layer must be carefully optimised so as not to compromise the performance of an APD device.

The following target specifications were defined to assess the feasibility of manufacturing SWIR APD arrays using Ge:

- 1) 1.55 μm uncooled operation
- 2) <20 ns rise time
- 3) Gain of >20, preferably 100.

4) Single Photon Counting

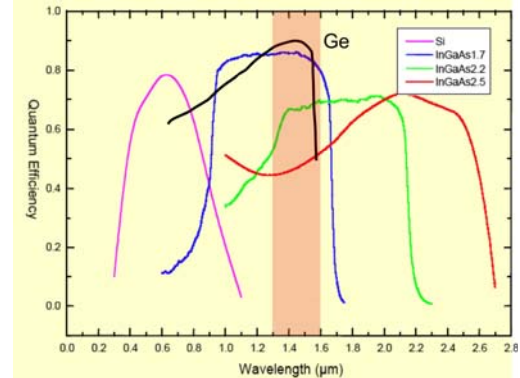


Figure 1 Absorption properties of some common materials



Figure 2: Cross section transmission electron microscopy (XTEM) image of germanium on silicon showing dislocations.

Substrate Preparation

For the formation of pure germanium it is possible to grow the layer directly onto silicon [2]. The initial growth must be performed at low temperature (around 400 °C) to prevent the germanium layer from becoming very rough. After a thin (~0.1 μm) layer has been grown the temperature is increased to around 700 °C. The low temperature layer, particularly close to the interface, has a high density of dislocations. Many of these annihilate when they encounter each other but there is still a great number remaining. The higher temperature of the upper layer promotes annihilation by supplying the thermal energy for dislocations to move, increasing the chance of them meeting. The density is still high though, greater than 10^8 cm^{-2} (figure 2). A subsequent anneal at a still higher temperature (> 800 °C) can reduce the dislocation density to approximately one tenth its previous value, typically $1 \times 10^7 - 3 \times 10^7 \text{ cm}^{-2}$.

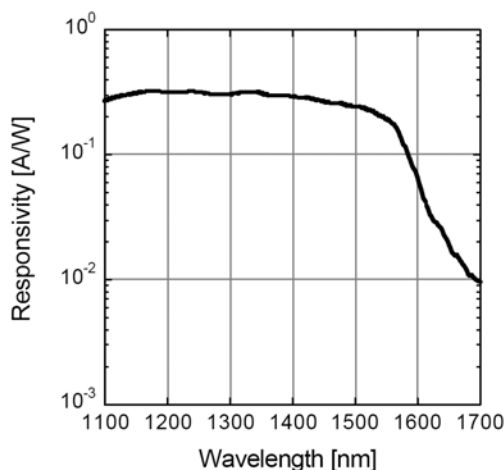


Figure 3: AdvanceSis Ge PIN diode responsivity.

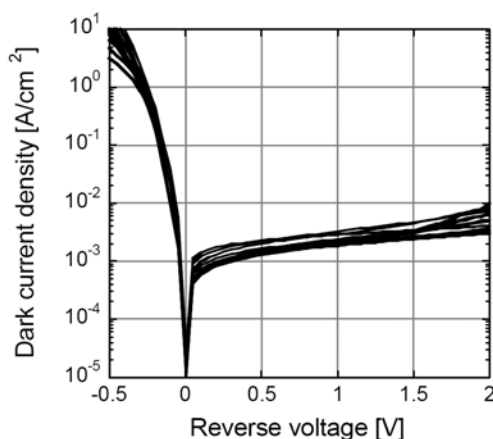


Figure 4: AdvanceSis Ge PIN diode dark current characteristics.

This two-temperature approach for depositing Ge tends to produce very smooth surfaces, the RMS (root mean square) roughness being typically less than 1 nm.

Figure 3 shows responsivity of PIN photodiodes formed in germanium grown by AdvanceSis on silicon using CVD. Figure 4 shows the dark currents of the same devices. These results are comparable to state-of-the-art devices formed in Ge grown using the same technique indicating that the material quality is good.

A mechanical rather than chemical technique for generating layers of Ge on a silicon substrate is wafer bonding. Many different materials can be directly bonded

together; the main requirement is that they are very smooth. The most common material system is silicon on oxide (SOI)[3] where one silicon wafer is bonded to a second which has a layer of SiO₂ on the front surface. The wafers are held together by hydrophilic, covalent and Van der Waals forces.

One of the wafers will be thinned to produce a layer anywhere between 0.1 μm to 10 μm in thickness. For thick layers it is sufficient to grind and chemically etch away most of one of the wafers. If a thin layer is required, a technique called *layer transfer* is commonly used. In this a weak point within the starting material is introduced. This then serves as a plane where, after bonding, the top bonded layer can be separated from the bulk of the donor wafer. Only a small amount of material then needs to be removed by grinding or etching.

The most common technique [4] is patented by Soitec. Here the weak point is created by implanting a high dose of hydrogen ions, forming micro-cavities across the wafer at a well-defined depth. After bonding, the wafers are heated which induces the weak plane to crack and cleave. One advantage of this and similar techniques is that the majority of the wafer remaining after the transferred layer is removed remains intact and can therefore be re-used.

If better control is required on the final thickness an etch-stop layer can be added. This could be a layer of different chemical composition, or a layer doped with electrically-active elements (such as boron in silicon).

For the current application it would be appropriate to transfer a layer of germanium onto a silicon substrate or vice versa. Although the bonded interface will still have dislocations and other defects, unlike the other techniques outlined in this section no dislocations will be generated in the bulk

of the Ge layer. If the source of the layer were a single-crystal substrate it is possible to achieve zero dislocations in the absorption region.

Since detector devices will most probably be formed in discrete areas, the techniques used to form a continuous layer across the whole of a silicon wafer may not be applicable. Instead techniques to deposit in areas defined by a SiO₂ mask may be required. In this case deposition occurs on silicon exposed through openings in the mask but not on the oxide mask itself. Techniques to deposit both germanium and silicon selectively were developed for this investigation and are now available, if necessary, for future work. Figures 5 and 6 show scanning electron microscopy (SEM) images of the selective germanium.

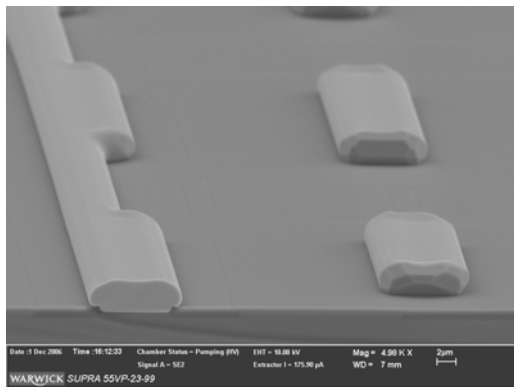


Figure 5: SEM image of germanium (the light-coloured raised areas) grown selectively within windows etched into a SiO₂ mask.

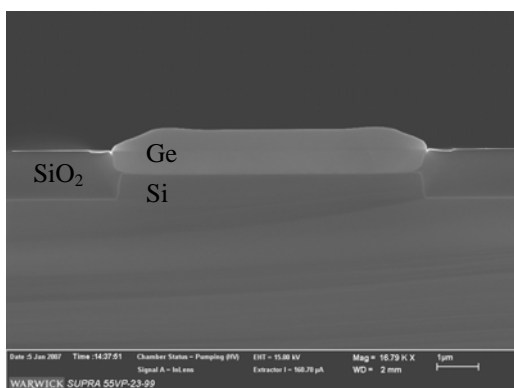


Figure 6: Cross-section SEM image of germanium grown selectively. In this case the Ge is thinner so that it does not grow over the SiO₂ at the edges.

Proposed Exploratory Device Designs

The starting substrate structure chosen is that illustrated in figure 7. The thick germanium layer is formed either by CVD epitaxial growth or by wafer bonding. Subsequent to the formation of the thick Ge layer the original wafer is bonded to a second “handle” wafer coated with a layer of SiO₂. The original Si wafer is then thinned to approximately 5 µm suitable for forming APD devices. Since the germanium is buried, existing expertise and conventional techniques for forming APDs in silicon can be used (with a consideration of the 938 °C melting temperature of Ge).

The substrate shown in figure 7 enables the possibility of implementing a standard planar shallow junction Geiger-mode APD in the silicon layer (figure 8) but with germanium used as the SWIR absorber. SWIR radiation will be incident from the top and will pass through the silicon mostly unabsorbed to reach the germanium layer. Photogenerated carriers from the Ge will then drift into the silicon avalanche multiplication region. Shallow junction detectors are a fairly well established technology [5] and so will use existing know-how. The only consideration is that the process for forming the APD devices must be modified to not use high temperatures which would damage the germanium layer.

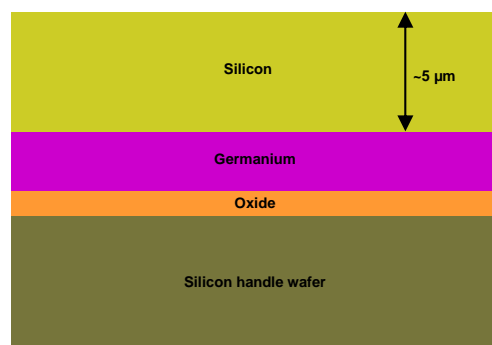


Figure 7: Germanium on silicon bonded to a second silicon / SiO₂ handle wafer. The silicon of the original wafer has been thinned to approximately 5 µm.

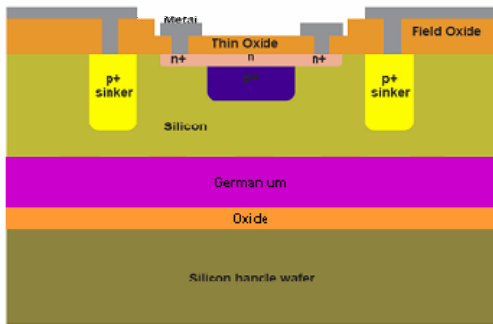


Figure 8: Planar Geiger-mode APD fabricated in the silicon layer from the original wafer.

The second option and perhaps the preferred structure for forming arrays of devices due to the reduced number of process steps and the improved proximity of neighbouring devices in an array is the Mesa-APD structure schematically illustrated in figure 9. These devices will be formed by etching away some of the upper silicon layer in the areas not forming APD devices.

This device also provides natural optical isolation between pixels due to the nature of the Mesa structure. It is anticipated that this is the most likely candidate for successful implementation of arrays of photon counting detectors operating in the short-wave infra-red (SWIR). The fabrication process for this structure is in general simpler, requiring fewer steps and lower temperatures.

Conclusion

It is considered feasible to form Avalanche Photodiodes for SWIR applications using germanium integrated onto a silicon platform. A starting substrate formed by a combination of CVD epitaxy and wafer bonding is proposed to form a buried Ge absorption layer. Known APD device structures can then be formed in the upper silicon layer with photogenerated carriers drifting from the Ge absorber to the Si multiplication region.

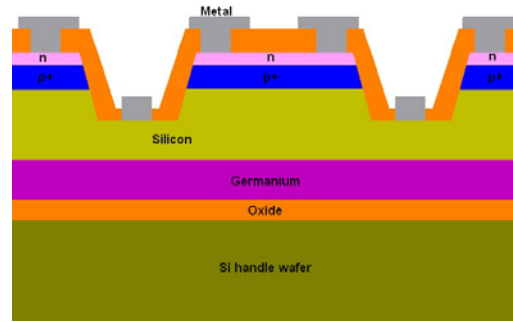


Figure 9: Mesa-type Geiger-mode APD fabricated in the silicon from the original wafer.

There is a question of what effect on device performance any dislocations in the germanium layer or the quality of the Ge / Si interface will have. In particular, there is a concern that dark current and dark counts will be high due to carrier generation associated with defects and work may be required to reduce the number of these defects. This warrants further investigation.

References

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Acknowledgements

The work reported in this paper was funded by the Electro-Magnetic Remote Sensing (EMRS) Defence Technology Centre, established by the UK Ministry of Defence and run by a consortium SELEX Sensors and Airborne Systems, Thales Defence, Roke Manor Research and Filtronic.