Claims:

1. A single photon avalanche diode (SPAD) device comprising:

a Si-based avalanche layer formed over an n-type semiconductor contact layer;

a p-type charge sheet layer formed in or on the avalanche layer, the p-type charge sheet layer having an in-plane width;

a Ge-based absorber layer, formed over the charge sheet layer and/or the avalanche layer, and overlapping the charge sheet layer, the Ge-based absorber layer having an in-plane width;

wherein, at least in one in-plane direction, the in-plane width of the Ge-based absorber layer is greater than the in-plane width of the p-type charge sheet layer.

2. A SPAD device according to claim 1 wherein in all in-plane directions, the in-plane width of the Ge-based absorber layer is greater than the in-plane width of the p-type charge sheet layer.

3. A SPAD device according to claim 1 or claim 2, further comprising:

a p-type semiconductor contact layer formed over the absorber layer, the p-type semiconductor contact layer having an in-plane width,

wherein at least part of the p-type semiconductor contact layer is formed substantially in register with at least part of the p-type charge sheet layer, with the Ge-based absorber layer interposed between them.

4. A SPAD device according to claim 3 wherein, at least in one in-plane direction, the in-plane width of the Ge-based absorber layer is greater than the in-plane width of the p-type semiconductor contact layer.

5. A SPAD device according to claim 3 wherein, in all in-plane directions, the in-plane width of the Ge-based absorber layer is greater than the in-plane width of the p-type semiconductor contact layer.

6. A SPAD device according to claim 3 wherein, in all in-plane directions, the in-plane width of the Ge-based absorber layer is greater than the in-plane width of the p-type semiconductor contact layer and greater than the in-plane width of the p-type charge sheet layer.

7. A SPAD device according to any one of claims 3 to 6 wherein the entire p-type semiconductor contact layer is formed substantially in register with at least part of the p-type charge sheet layer.

8. A SPAD device according to any one of claims 1 to 9 wherein the Ge-based absorber has a sidewall in said in-plane direction and the charge sheet layer has a lateral edge in said in-plane direction, and either:

(a) when the Ge-based absorber has a thickness of at least 1 μm, the distance in the in-plane direction between the lateral edge of the charge sheet layer and the sidewall of the Ge-based absorber is at least 1 μm greater than the thickness of the Ge-based absorber; or

~~(b) when the Ge-based absorber has a thickness of less than 1 µm, the distance in the in-plane direction between the lateral edge of the charge sheet layer and the sidewall of the Ge-based absorber is at least 1.0 µm.~~

~~9. A SPAD device according to any one of claims 1 to 8 wherein the distance in the in-plane direction between the lateral edge of the charge sheet layer and the sidewall of the Ge-based absorber is at least 5 µm.~~

~~10. A SPAD device according to any one of claims 3 to 7, or claims 8 to 9 as dependent on any one of claims 3 to 7, wherein the p-type semiconductor contact layer has a lateral edge in said in-plane direction and the charge sheet layer has a lateral edge in said in-plane direction, and either:~~

~~(c) when the width of the charge sheet is at least 25 µm, a distance in the in-plane direction between the lateral edge of the charge sheet layer and the lateral edge of the p type semiconductor contact layer is at least 2 µm; or~~

~~(d) when the width of the charge sheet is less than 25 µm, a distance in the in-plane direction between the lateral edge of the charge sheet layer and the lateral edge of the p-type semiconductor contact layer is at least 1 µm.~~

~~11. A SPAD device according to any one of claims 1 to 10 wherein the charge sheet layer has a maximum doping concentration at a depth in the range 10-100 nm from the surface of the Si-based avalanche layer.~~

~~12. A SPAD array comprising at least a 1 x 2 arrangement of SPAD devices each according to any one of claims 1 to 11 and formed on a common substrate.~~

~~13. A SPAD array according to claim 12 wherein the respective Ge-based absorber layers of adjacent SPAD devices are laterally isolated by:~~

~~(i) etching of a continuous Ge-based absorber layer to at least the depth of the p-type charge sheet layer in order to form the respective Ge-based absorber layers of adjacent SPAD devices; or~~

~~(ii) doping of a continuous Ge-based absorber layer to at least the depth of the p-type charge sheet layer in order to form the respective Ge-based absorber layers of adjacent SPAD devices; or~~

~~(iii) selective area growth of the respective Ge-based absorber layers within patterned electrically insulating layers in order to form the respective Ge absorber layers of adjacent SPAD devices.~~

~~14. A LIDAR system comprising a source of light of wavelength in the range 0.9 – 2.0 µm and a SPAD device according to any one of claims 1 to 11 or a SPAD array according to any one of claims 12 to 13.~~

~~15. Use of a SPAD device according to any one of claims 1 to 11 or a SPAD array according to any one of claims 12 to 13 in the detection of at least one photon with wavelength in the range 0.9-2.0 µm.~~

~~16. A method of manufacture of a SPAD device according to any one of claims 1 to 11 wherein the p-type charge sheet layer is formed by selective area implantation into the Si-based avalanche layer.~~

~~17. A method according to claim 16 wherein the charge sheet layer is activated by annealing at a temperature of at least 850°C, before deposition of the Ge-based absorber layer.~~

~~18. A method according to claim 16 or claim 17 wherein at least one upper and/or side surface of the Ge-based absorber layer is passivated.~~

~~19. A method according to claim 18 wherein the passivation is provided by a GeO_2 layer thermally grown and protected by an Al_2O_3 layer.~~

Claims:

1. A single photon avalanche diode (SPAD) device comprising:

a Si-based avalanche layer formed over an n-type semiconductor contact layer;

a p-type charge sheet layer formed in or on the avalanche layer, the p-type charge sheet layer having an in-plane width;

a Ge-based absorber layer, formed over the charge sheet layer and/or the avalanche layer, and overlapping the charge sheet layer, the Ge-based absorber layer having an in-plane width;

characterized in that

at least in one in-plane direction, the in-plane width of the Ge-based absorber layer is greater than the in-plane width of the p-type charge sheet layer.

2. A SPAD device according to claim 1 wherein in all in-plane directions, the in-plane width of the Ge-based absorber layer is greater than the in-plane width of the p-type charge sheet layer.

3. A SPAD device according to claim 1 or claim 2, further comprising:

a p-type semiconductor contact layer formed over the absorber layer, the p-type semiconductor contact layer having an in-plane width,

wherein at least part of the p-type semiconductor contact layer is formed substantially in register with at least part of the p-type charge sheet layer, with the Ge-based absorber layer interposed between them.

4. A SPAD device according to claim 3 wherein, at least in one in-plane direction, the in-plane width of the Ge-based absorber layer is greater than the in-plane width of the p-type semiconductor contact layer.

5. A SPAD device according to claim 3 wherein, in all in-plane directions, the in-plane width of the Ge-based absorber layer is greater than the in-plane width of the p-type semiconductor contact layer.

6. A SPAD device according to claim 3 wherein, in all in-plane directions, the in-plane width of the Ge-based absorber layer is greater than the in-plane width of the p-type semiconductor contact layer and greater than the in-plane width of the p-type charge sheet layer.

7. A SPAD device according to any one of claims 3 to 6 wherein the entire p-type semiconductor contact layer is formed substantially in register with at least part of the p-type charge sheet layer.

8. A SPAD device according to any one of claims 1 to 7 wherein the Ge-based absorber has a sidewall in said in-plane direction and the charge sheet layer has a lateral edge in said in-plane direction, and either:
(a) when the Ge-based absorber has a thickness of at least 1 μm, the distance in the in-plane direction between the lateral edge of the charge sheet layer and the sidewall of the Ge-based absorber is at least 1 μm greater than the thickness of the Ge-based absorber; or
(b) when the Ge-based absorber has a thickness of less than 1 μm, the distance in the in-plane direction between the lateral edge of the charge sheet layer and the sidewall of the Ge-based absorber is at least 1.0 μm; optionally
wherein the distance in the in-plane direction between the lateral edge of the charge sheet layer and the sidewall of the Ge-based absorber is at least 5 μm.

9. A SPAD device according to any one of claims 3 to 7, or claim 8 as dependent on any one of
claims 3 to 7, wherein the p-type semiconductor contact layer has a lateral edge in said in-plane direction and the charge sheet layer has a lateral edge in said in-plane direction, and either:
(c) when the width of the charge sheet is at least 25 μm, a distance in the in-plane direction between the lateral edge of the charge sheet layer and the lateral edge of the p-type semiconductor contact layer is at least 2 μm; or
(d) when the width of the charge sheet is less than 25 μm, a distance in the in-plane direction between the lateral edge of the charge sheet layer and the lateral edge of the p-type semiconductor contact layer is at least 1 μm; optionally wherein the charge sheet layer has a maximum doping concentration at a depth in the range 10-100 nm from the surface of the Si-based avalanche layer.

10. A SPAD array comprising at least a 1 x 2 arrangement of SPAD devices each according to any one of claims 1 to 9 and formed on a common substrate.

11. A SPAD array according to claim 10 wherein the respective Ge-based absorber layers of adjacent SPAD devices are laterally isolated by:
(i) etching of a continuous Ge-based absorber layer to at least the depth of the p-type charge sheet layer in order to form the respective Ge-based absorber layers of adjacent SPAD devices; or
(ii) doping of a continuous Ge-based absorber layer to at least the depth of the p-type charge sheet layer in order to form the respective Ge-based absorber layers of adjacent SPAD devices; or
(iii) selective area growth of the respective Ge-based absorber layers within patterned electrically insulating layers in order to form the respective Ge absorber layers of adjacent SPAD devices.

12. A LIDAR system comprising a source of light of wavelength in the range 0.9 – 2.0 μm and a SPAD device according to any one of claims 1 to 9 or a SPAD array according to any one of claims 10 to 11.

13. Use of a SPAD device according to any one of claims 1 to 9 or a SPAD array according to any one of claims 10 to 11 in the detection of at least one photon with wavelength in the range 0.9-2.0 μm.

14. A method of manufacture of a SPAD device according to any one of claims 1 to 9 wherein the p-type charge sheet layer is formed by selective area implantation into the Si-based avalanche layer.

15. A method according to claim 14 wherein the charge sheet layer is activated by annealing at a temperature of at least 850°C, before deposition of the Ge-based absorber layer, optionally wherein at least one upper and/or side surface of the Ge-based absorber layer is passivated, optionally wherein the passivation is provided by a GeO_2 layer thermally grown and protected by an Al_2O_3 layer.