In the preparation of APD device, we have prepared APD device of $n^+/n/p/p^+$-Poly-$Si_{0.82}Ge_{0.18}$/ SiO_2/Si structure. In order to compare characteristics of Poly-$Si_{0.82}Ge_{0.18}$ thin film, we perform annealing on the APD device. The experimental result shows that for an APD device, through an annealing at 800℃ in the N_2 environment for 30 minutes, and at a fixed optical illumination of 3.0μW and a reverse bias of 27V, the measured photocurrent is 143.75μA, response coefficient47.92 A/W , quantum efficiency 82.94%, and a photo dark current ratio of 142.75. From the experimental result comparison, we found that APD device annealed at 800℃ in N_2 environment for 30 minutes has a response photocurrent 7.67 times as compared to that of non-annealed APD device, this is believed to be the best parameter in the preparation of APD device.

Si material, due to its maturity in manufacturing technology and low cost, has played a vital role in the semiconductor industry; but its electrical and optical property is inferior to normal Ⅲ-Ⅴ semiconductor materials, this greatly reduces its application in the optoelectronic and communication industry.

Since Ge has a smaller bandgap and a larger electron/hole mobility (about 3~4 times) than Si, besides, both has very similar lattice structure, therefore, through the growth of Si/SiGe crystalline layer of appropriate Ge content and accompanied with the well developed Si technology, we can prepare device with improved characteristics（for example, larger driving current）.

The growth of SiGe epitaxial film is an important new technology in recent years. The energy bandgap and characteristic of SiGe compound will change along with the increase or decrease of Ge content, the hetero-junction structure formed between SiGe epitaxial film and Si allows more design space for high performance semiconductor device. Since Poly-$Si_{1-x}Ge_x$ thin film needs lower process deposition temperature, higher mobility, higher resistance temperature coefficient and Si-matched manufacturing technology as compared to poly-crystalline silicon, therefore, it has gradually replaced poly Si in the applications such as: optoelectronic device, the gate electrode of CMOS device, thin film transistors, thermocouple and far infrared thermal radiation sensors.

The lattice constant of pure Si is 5.43 Å, and 5.65 Å for pure Ge, the difference is about 4.2%, this mismatch of 4.2% in the lattice constant makes it difficult to grow epitaxially SiGe thin film on Si substrate. Since Ge has a lattice constant about 4.2% longer than that of Si crystal, therefore, a strain in the SiGe layer is necessary to let it become smaller in the horizontal lattice constant in order to match Si but become larger in the growth direction. Strain of this structure is called compressive strain, the grown SiGe layer thickness needs to be controlled below critical thickness so that dislocation defect which is formed due to strain energy release can be prevented.

Since the difference in lattice constant between Si and Ge is about 4.2%, this mismatch of 4.2% in the lattice constant makes it difficult to grow epitaxially SiGe thin film on Si substrate, the process temperature in the early research is too high (>900 ℃) which could easily induce strain energy release in the SiGe thin film and in turn cause the so-called islanding phenomenon. A breakthrough is made until the low temperature epitaxial growth technology (<700℃) which is developed in the 80's. Initially, molecular beam epitaxy (MBE) is used to grow thin film, it opens new researches in the related materials and device applications, later on, the ultra high vacuum chemical vapor deposition (UHV/CVD) technology developed by IBM and the rapid thermal chemical vapor deposition (RTCVD) developed by Stanford University have further improved the epitaxial film quality, this also accelerates the technology development of SiGe hetero-junction bipolar transistor (HBT). Such device can be operated at very high speed (GHz), its major application is in the RF communication product in order to improve the traditional Si device characteristics, most importantly, it is compatible to traditional Si process, therefore, production cost can be greatly reduced, it's thus of very high application potential. Recently, one German company announces it will start producing SiGe communication IC product, there are also many companies in US, Canada and Japan want to join the market, we can thus see its great potential. Related researches in poly-SiGe starts in early 90s, it is deposited mainly on a surface-insulated substrate, for example, glass or thermal oxide, since the deposition condition is not as strict as epitaxial film, therefore, conventional LPCVD method can be used, the low manufacturing cost is thus a good advantage. The early focus is on the study of thin film transistor (TFT), since conventional deposition of ploy-Si needs to be at temperature higher than

620℃ in order to get poly crystalline thin film which does not contain amorphous phase, therefore, high cost quartz substrate has to be used,. Since the deposition of poly-SiGe is lower than poly-Si, LPCVD can thus be used to grow the film on low cost glass substrate.

Poly-Si$_{1-x}$Ge$_x$ can be grown by using conventional CVD method, as compared to the high temperature, high vacuum, low deposition rate and high equipment cost in the epitaxy of single crystal SiGe, poly-SiGe can use low cost equipment and low thermal budget to grow film at high deposition rate. Since poly-SiGe has less trouble of dislocation accumulation, it thus has no limitation on critical thickness, the Ge content can thus be easily increased, besides, poly-SiGe normally has a resistance about 1-2 order of magnitude lower than single crystal SiGe (poly-SiGe can easily generate defect induced state which in turn limit the Fermi energy to close to the valence band), therefore, poly-SiGe is suitable to be used for the manufacturing of devices such as : TFT, MOS, etc., without too much change in the device design and process, TFT and MOS device can use poly-SiGe film with Ge content lower than 50% (too much Ge could have the troubles such as low melting temperature oxide layer instability, etc.), poly-SiGe with Ge content higher than 50% can be used as the active layer in the photo detector.

When a thin silicon layer is grown on top of the SiGe/Si structure, the thermal stability of the whole structure can be further enhanced. The valence band of the medium SiGe layer of this structure is higher than Si, but conduction band is lower than Si, the energy band formed makes it suitable to be used in the manufacturing of n-p-n type SiGe Heterojunction Bipolar Transistor or SiGe HBT, it is the most important epitaxial structure currently in real application. This device can be operated at high frequency (GHz), it is mainly applied in RF communication product to improve the device characteristic of conventional Si device, besides, it can be compatible to conventional Si process, the manufacturing process can thus be greatly reduced, it is of great application potential. Through a research of over 20 years, SiGe materials and related device technology is now becoming the most important solution in the high speed communication market. SiGe HBT can operate at low power, it provides superior RF and microwave performance which not only exceeds traditional Si technology but also challenges traditional Ⅲ-Ⅴ compound semiconductor device technology in the related fields. Recently, due to the development in doping technology, a much thinner but highly doped base layer can be formed, the communication system which uses related technology can thus transfer at speed above 40Gb/s. In the manufacturing process, it is compatible and can be integrated to the current mature CMOS technology, besides, passive components can be integrated onto the same chip to enhance the effectiveness of the whole communication system and reduce the manufacturing process.

When photo detector absorbs light of specific wavelength, many electron-hole pairs (EHP) will be generated due to photo excitation, after separated and accelerated by the electric field, these EHPs will be collected by the ohmic contact at both ends to form photo current, through the interaction at the outer circuit, an output electrical signal is then generated.

Avalanche Photodiode (APD) and PIN photodiode are two most widely used photodiodes. APD works in visible light and infrared range has two major functions: the first one is the normal optical wave signal detection; the second one is more special, it is the function that PIN photodiode does not possess, when APD is in operation, the internal carriers are under the effect of avalanche multiplication, the detected signal is thus amplified, therefore, APD has very high sensitivity, it is commonly used in optical signal detection in optical fiber communication.

Photo detectors can roughly be divided into Schottky, p-n, p-i-n, avalanche, metal-semiconductor-metal (MSM), CCD, MOS, etc. Among them, avalanche photodiode, APD, has advantages such as: large current gain, fast response, high quantum efficiency and microwave frequency (100GHz), etc., this study thus use this device as the photo detector in this experiment.

Thermal evaporation is used in this experiment for the metal deposition, its main principle is to heat the evaporated metal, the atoms then get evaporated and coat onto the substrate surface. The e-gun evaporation system is as shown in figure 2-4.

Put the cleaned substrate on top of the crucible for about 20 cm distance, Al of 99.99% purity is used as the target of the e-gun evaporation, pump the system to below 5×10^{-5}torr to start the evaporation. Thermionic filament is used to provide current and generate electron beam, after the electron beam is accelerated by the high electric field, it will bombard the target metal, its energy is high enough to evaporate the target metal and let the evaporated metal coat the substrate.

The annealing system is as shown in figure 2-5. First, the temperature is raised to the temperature desired for the experiment, input the needed gas when it gets stable, nitrogen (N_2) is used in this experiment. Then put the specimen on the wafer boat inside a quartz tube, then push it slowly into appropriate location and close the quartz tube immediately. Wait until the annealing temperature needed for the experiment is reached, open the quartz tube to take out the wafer boat.

Related exposure and microlithography technology is used for this experiment to make the desired pattern for the photo-sensitive device. First, Spin Coater is used to coat photo resist onto the specimen, then soft-bake it in the oven for 10 minutes, then exposure machine is used to transfer the pattern from the photo mask to the specimen.

When atom absorbs large energy from outside, it will be promoted from ground state to the excited state, at this moment, electron in the inner shell of the atom will move to outer shell or get emitted due to the energy absorption. When the inner shell loses electron, since the inner shell of the atom has lower potential energy, the outer shell electron will then move toward inner shell. When the outer shell electron of the atom moves toward the empty orbital of the inner shell electron, the energy released is the energy difference between the two energy levels, the radiation formed by this energy is X-ray. The spacing between lattice plane of normal crystal is close to the wavelength of X-ray. Therefore, crystal could easily cause diffraction to X-ray. The followings are the necessary conditions of diffraction, it is called Bragg Diffraction Law.

Energy Dispersive X-ray Spectrometer, EDS, has high resolution, besides, it can select arbitrarily tiny area (~100Å) to do chemical composition quantitative analysis, it is the most widely used X-ray detection technique, it is compatible to SEM and can detect composition. Its principles are proposed by Cliff and Lorimer, assume a compound contains both element A and B (the percentage is C_A and C_B respectively), when it reacts with high energy electron beam, two corresponding characteristic X-rays will be generated with strength I_A and I_B respectively, then C_A/C_B and I_A/I_B can be represented by a relationship.

Wherein K_{AB}, at special voltage (the voltage used by SEM) is a constant, it is independent of the specimen thickness and chemical composition. In multiple element system, when all elements are represented as percentage (that is, $\Sigma C_N=100$), then the above equation can be applied to multiple element system to represent the relationship between the detected X-ray strength of any element and its corresponding element percentage.

From the roughness curve of the specimen surface, a standard length L is intercepted, the center of the roughness curve is used as a base, the center line is defined as x axis, a line perpendicular to this center line is defined as y axis, then the roughness curve can be represented by y=f(x), the center line average roughness R_a can then be calculated from the following equation.

Transparent conductive film indium tin oxide In_2O_3: Sn (ITO) is n-type wide band-gap semiconductor with energy gap about 3.55eV-3.75eV. The principle to enhance the electrical conductivity of indium tin oxide film is to use the added Sn to replace In, the amount of vacancy in the crystal can decide the carrier concentration, if the tetra-valent Sn replaces tri-valent In, one more electron can be supplied, however, the formation of oxygen vacancy will induce defect structure in the crystallography which in turn decreases the electron carrier mobility, however, when each oxygen vacancy is generated, two more electrons become extra, the carrier concentration is thus increased, these two properties can effectively reduce the resistance of the material.

Impurity elements such as Zn, Te, Sb, are commonly used as dopants to improve the electrical conductivity of In_2O_3, the most effective one is Sn, that is (In_2O_3：Sn, ITO), a theoretical calculation on the carrier concentration is about $3.0 \times 10^{20} \times C_{sn}$(at.%), C_{sn} is the tin concentration, however, the carrier concentration does not increase as expected as doping concentration increases, so is the electrical conductivity, Benamar et al. propose that 5% tin creates the optimum resistivity 4×10^{-5} Ω-cm, besides, Bisht et al. thinks that 3% tin creates the minimum resistivity 2.5 $\times 10^{-4}$ Ω-cm.

In addition to increasing the carrier to improve the electrical conductivity of In_2O_3, some people try to improve it through the improvement of carrier mobility, Kamei et al. deposit ITO film on YSZ (yttria stabilized zirconia) single crystal to get preferentially oriented thin film, but the measured carrier mobility is not too much different than that of randomly oriented poly crystalline thin film, there is no relationship between the electron mobility and the existence of preferential orientation in the thin film. The effective way of enhancing the electrical conductivity of thin film is through the doping of other element to create thin film with defects, in turn, the electrons contributed by these defects are used to increase the electrical conductivity of the materials.

Since ITO material is highly transparent (＞80%) and of low resistivity ($<10^{-4}\Omega$-cm), it is commonly used in daily optoelectronic products, for example, as the conductive film in LCD, PDP and OLED, which are applied in the products such as notebook computer, PDA and cellular phone.

The magnitude of photo current will change with the strength of optical illumination, the optical sensitivity of photodiode can thus be deduced here.

The quantum efficiency η of p-n junction photodiode can be used to represent the photoelectric effect of the diode. The quantum efficiency is defined as the generated electron-hole pair number for each incident photon.

The key factor that affects quantum efficiency is the optical absorption coefficient of the material, and the optical absorption coefficient is closely related to the incident wavelength.

For the tunneling time effect, it can be solved by p-i-n photodiode. p-i-n photodiode has a depletion layer (intrinsic layer) thickness which can be modulated in order to obtain optimum quantum efficiency and frequency response.

Annealing is a very important step in the semiconductor process. In this experiment, many processes will need annealing technology, for example, the thermal annealing treatment of poly-SiGe film to improve its crystalline situation, the thermal annealing drive-in process after ion implantation for poly-crystalline-SiGe film in order to let the dopants diffuse, the thermal annealing treatment after the contact of the electrode of APD device and poly-SiGe film in order to let the interface form an Ohmic Contact, etc.

Before the close contact of metal and semiconductor, there is no electron transfer, there is no contact potential generated too; if two materials get close contact, contact potential will be generated at the junction because of the difference between the two work functions, this is called Schottky barrier. In the Schottky barrier, current transfer is mainly completed by majority carrier, this is quiet different from p-n junction which relies on minority carrier for conducting current. Therefore, we need to turn the metal-semiconductor junction into ohmic contact through annealing treatment. When the contact resistance of a metal-semiconductor contact is negligible as compared to the semiconductor itself, it can be defined as ohmic contact. Good ohmic contact will not significantly reduce the device performance, meanwhile, the voltage drop generated when required current passes through it is smaller than the voltage drop across the active area of the device.

There are three key factors in the annealing processes: that is, temperature, time and the input gas. Temperature represents the energy supplied to the atoms, appropriate annealing temperature and time can make the materials property better. Temperature too high or overtime could induce defects in the materials, but temperature too low and time too short, good materials property could not be obtained. How to make a tradeoff is a crucial topic.

From the results in figure 5-9 to 5-12, we can deduce the photo dark current ratio of APD device made by all kinds of parameters, its definition is “(photo current-dark current)/dark current”. Since the photo dark current ratio is directly related to the noise, therefore, photo dark current ratio is a very important index for a photo detector.

Exponent n is related to the impurity distribution in the semiconductor material and the wavelength of the incident light. The junction voltage $V_J \equiv (V - I_D R)$, under normal operation, is usually smaller than V_{BR}, if V_J approaches V_{BR}, the avalanche multiplication factor M of the carrier will become very large, the normal M value of APD is between 30 to 100. We can find from figure 5-22, the M value of APD prepared by this experiment does not show obvious rising trend at low V_J/V_{BR}, it only rises slowly when the V_J/V_{BR} value rises; but when V_J/V_{BR} approaches 1, M value will rise rapidly, or even approaches infinity. Among them, M is a maximum when n=3, then in a decreasing order for n=4, 5, 6.

This study shows a successful preparation of APD using poly-SiGe thin film. The Si and Ge ratio for the poly-SiGe thin film in this study is 0.82：0.18. From the experiment, we find that the poly-SiGe thin film deposited by LPCVD still has bas crystalline status, only very weak crystallographic facets exist; therefore, multiple annealing parameters are designed in this study in order to observe the effect of annealing on the poly-SiGe thin film material characteristics. From the experiment, we find that annealed poly-SiGe thin film will have more perfect crystalline facets; the optimum annealing parameters are at 800℃ for 30 minutes in N_2 environment.

Indium tin oxide (ITO) is used as the transparent conductive layer of the anode of the APD. ITO thin film is prepared by evaporation method in this experiment. We find from the experiment that ITO thin film has improved material through methods such as substrate heating, annealing treatment. Among them, annealing treatment has more effect than substrate heating on reducing the sheet resistance of ITO. The ITO annealing parameters adopted by this experiment are: annealing temperature of 300℃, annealing time of one hour and under N2 environment. Through the measured results from this experiment, such as: optical transmission, XRD, SEM and sheet resistance measurement, we conclude the optimum conditions are: substrate temperature 100℃, annealed at 300℃ for 1 hour, the gas environment is N_2, ITO thin film made by such conditions is the most suitable one for the anode of the transparent conductive layer of APD.

In the preparation part of APD, we have measured the photo current and dark current at different optical illumination, meanwhile, the response coefficient, quantum efficiency, photo dark current ratio are converted too. Since the annealing parameters will affect the poly-SiGe thin film which composes the device, we thus design several groups of parameters in order to observe their effects on optical characteristics. We find from the experiment, APD device prepared under N_2 environment, at 800℃ for 30 minutes, when measured at optical illumination of 3.0μW, reverse bias of 27V, will have a photo current of 143.75μA, response time of 47.92 A/W, quantum efficiency of 82.94%, photo dark current ratio

142.75; the response photo current is 7.67 times as compared to that of non-annealed APD device, this is believed to be the best parameter in the preparation of APD device.

Use traditional Si as optoelectronic device, its electrical and optical property is inferior to normal Ⅲ-Ⅴ semiconductor materials. However, III-V semiconductor is too expensive, this greatly reduces its application as semiconductor devices. Since Germanium (Ge) has higher electron/hole mobility (about 3~4 times) as compared to Si, we therefore start investigating the application of Si_xGe_x as optoelectronic device. Since traditional LPCVD can be used in the preparation of poly-SiGe, besides, the process is compatible to normal poly-Si process; therefore, if we can device with performance close to Ⅲ-Ⅴ semiconductor, it would be good news to the future semiconductor industry.

Although APD device prepared by poly-SiGe film has been successfully completed in this experiment, however, the process temperature is too high and a lot of defects could be generated on the surface. Lower temperature process can reduce epitaxial defects and have the devices prepared on low cost glass substrate for large area growth. For the current growth technology, such as: LPCVD, RTCVD, UHVCVD and Excimer Laser Annealing, ELA, etc. , they all have process temperatures higher than 500℃, thus, glass substrate process can not be applied in them. Therefore, how to develop low temperature poly-SiGe thin film process is really an important topic.