

SILICON GERMANIUM MULTI QUANTUM
WELLS FOR HIGH EFFICIENCY
OPTOELECTRONIC DEVICES

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ABSTRACT

SILICON GERMANIUM MULTI QUANTUM WELLS FOR HIGH EFFICIENCY OPTOELECTRONIC DEVICES

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Silicon (Si) based complementary metal-oxide-semiconductor (CMOS) technology provides a low cost platform and reproducible processing for electronic signal processing and electronic industry has significantly flourished in terms of increased device densities and speeds. All the same, advanced CMOS processes associated with the very large scale integrated (VLSI) circuits are required for the fabrication of today's advanced microprocessors comprising billions of transistors per single chip with higher operational data rates. Herein, increasing trend for the speed of current circuits is hampered due to the delays of electrical interconnects that basically arise from RC factor. Signal attenuation due to power dissipation and electromagnetic interference issues are further physical bottlenecks that affect the performance of current technology. At this point, an idea proposes the development of optical interconnect network layers on Si CMOS circuitry operating at telecommunications wavelength range (~ 1.3 - $1.5 \mu\text{m}$). This promising conception enables optical information processing and offers a platform that overcomes the physical restrictions of electrical interconnects. Si based optoelectronic devices are near-infrared-blind due to large indirect ($\sim 1.12 \text{ eV}$) and direct band gap ($\sim 3.4 \text{ eV}$) energies. To date, III-V compounds and especially InGaAs based detectors are "state-of-the-art" optical devices that are used for near-infrared (NIR) applications. However, due to high material cost and difficult integration with Si CMOS technology they

have limited market growth. At this point, germanium (Ge) is a promising candidate for NIR applications with its suitable indirect (~ 0.66 eV) and direct (~ 0.8 eV) band gap, which overcomes spectral limitations of Si. Additionally, lattice mismatch ($\sim 4.2\%$) problem among Si and Ge is worked out by novel heteroepitaxial growth technique (*MHAH*), which reduces the threading dislocations and enables the monolithic integration with conventional CMOS technology. For the scope of the thesis, fabrication, material characterization and device characterizations of *p-i-n* photodetector and electro-absorption modulator architectures, which are the key elements of a basic optical interconnect structure, are performed. Ge/Si_xGe_{1-x} multi quantum well (MQW) structures are utilized in the intrinsic layer to exploit the electro-absorption mechanism of quantum-confined Stark effect (QCSE). Represented photodetectors exhibit low dark current (~ 5 mA/cm² at -1 V) and high responsivity (~ 0.33 A/W at 1310 nm and 0 V). Demonstrated electro-absorption modulators exhibit very high absorption coefficient contrast (3.41 at 1550 nm and 3 V) especially for conventional C-band (1530-1565 nm) telecommunication wavelength range and low insertion loss (0.2 dB at 1540 nm). Modulation performance is highly comparable with the electro-absorption modulators based on direct gap III-V compounds at the wavelength range of interest. Demonstrated photodetector and electro-absorption modulators are the high performance building blocks of an optical interconnect system.

Keywords: SiGe, photodetector, electro-absorption modulator, quantum well, quantum-confined Stark effect, optical interconnect

ÖZET

SİLİSYUM GERMANYUM ÇOKLU KUANTUM KUYULARI İÇEREN YÜKSEK VERİMLİ OPTOELEKTRONİK AYGITLAR

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Elektrik ve Elektronik Mühendisliği Bölümü Yüksek Lisans

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Silisyum (Si) tabanlı tümler metal-oksit-yarıiletken (CMOS) teknolojisi elektronik sinyal işleme için düşük maliyetli ve tekrarlanabilir bir üretim ortamı sağlar. Elektronik endüstrisi aygıt hızları ve yoğunlukları göz önüne alındığında önemli ölçüde gelişti. Bununla birlikte, bugünün tek bir tümdevrede yüksek işlemsel veri hızına sahip milyonlarca tranzistörler içeren mikroişlemcilerin fabrikasyonu için çok büyük çapta tümleşik (VLSI) elektronik devreler içeren gelişmiş CMOS işlem süreçleri gerekmektedir. Bu noktada, bugünün devrelerinin artan hız eğilimi elektriksel arabağlantıların RC çarpanından kaynaklanan gecikmeler nedeniyle büyük ölçüde duraksama yaşadı. Güç yitimi ve elektromanyetik girişim sorunlarından kaynaklanan sinyal zayıflaması bugünün teknolojisinin başarımını etkileyen fiziksel engellerdir. Bu noktada, Si CMOS devrelerinin üzerine iletişim dalga boylarında çalışan ($\sim 1.3-1.5 \mu m$) optik arabağlantı ağları kurulması fikri ön plana çıkar. Bu gelecek vaat eden fikir elektriksel bağlantıların fiziksel engellerini ortadan kaldıran optik bilgi işleme ortamı sunar. Si tabanlı optoelektronik aygıtlar indirekt ($\sim 1.12 \text{ eV}$) ve direkt ($\sim 3.4 \text{ eV}$) yasak bant enerjileri nedeniyle yakın kızılberisi dalgaboylarında kördür. Bugüne kadar, III-V grubu bileşikler ve özellikle InGaAs tabanlı algılayıcılar yakın kızılberisi uygulamalar için en gelişmiş aygıtlardır. Fakat,

malzeme maliyetlerinin yüksekliđi ve Si CMOS teknolojisiyle tümleşim zorlukları nedeniyle sınırlı piyasa büyümesine sahiptir. Bu noktada, Germanyum (Ge), indirekt (~ 0.66 eV) ve direkt (~ 0.8 eV) yasak bant enerjileri sayesinde Silisyumun spektral sınırlamalarının üstesinden gelerek yakın kızılberisi dalgaboylarındaki uygulamalar için umut vaat eder. Ayrıca, dislokasyonları azaltan ve geleneksel CMOS teknolojisiyle tektaş tümleşimi sağlayan yeni geliştirilmiş bir heteroepitaksi yöntemi (*MHAH*) sayesinde Si ve Ge arasındaki örgüsel uyumsuzluk sorunu çözülmüştür. Bu tez kapsamında, optik arabađlantı yapılarının temel öğeleri olan *p-i-n* fotoalgılayıcı ve elektrosođrulma kipleycisi mimarilerinin fabrikasyon, aygıt ve malzeme karakterizasyonu gerçekleştirildi. Bir elektrosođrulma mekanizması olan kuantum sınırlamalı Stark etkisini (QCSE) kullanmak amacıyla Ge/Si_xGe_{1-x} çoklu kuantum kuyusu (MQW) yapıları *p-i-n* mimarilerinin katkısız kısımlarında kullanılmıştır. Gösterilen fotoalgılayıcılar düşük karanlık akımı (~ 5 mA/cm² ve -1 V) ve yüksek duyarlılık (~ 0.33 A/W, 1310 nm ve 0 V) sergiledi. Gösterilen elektrosođrulma kipleycileri özellikle C-bantı (1530-1565 nm) iletişim dalgaboyu alanında olmak üzere çok yüksek sođrulma katsayısı kontrastı (3.41, 1550 nm ve 3 V) sergiledi. Alakalı dalga boylarındaki III-V tabanlı elektrosođrulma kipleyciler ile çok benzer kiplenim başarıları sağlandı. Gösterilen fotoalgılayıcılar ve elektrosođrulma kipleycileri optik arabađlantı sistemlerinin yüksek başarılı yapıtaşlarıdır.

Anahtar Kelimeler: SiGe, fotoalgılayıcı, elektrosođrulma kipleycisi, kuantum kuyusu, kuantum sınırlamalı Stark etkisi, optik arabađlantı

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Chapter 1

Introduction

This thesis describes our recent developments on and contributions to complementary metal-oxide-semiconductor (CMOS) compatible optoelectronic device technology in terms of fabrication, characterization and analysis of novel devices. This chapter gives an overview of the problem and our motivation for carrying forward this work.

1.1 Problem Statement

Advances in the very large scale integration (VLSI) with the established Si CMOS technology have dramatically increased the device densities and speeds [1]. The traditional electrical interconnects based on Copper (Cu) metal wires and Aluminum (Al) interconnect lines mainly suffer from i) bandwidth limitation, ii) signal attenuation due to power dissipation, iii) electromagnetic interference issues [1-5]. These physical bottlenecks are the limiting factors for the performance of the current VLSI technology. According to the approach in 1984, Goodman *et al.* [2] have drawn attention by claiming that the speeds of CMOS circuits will be limited by interconnection delays of the devices. Meindl [3], similarly and exhaustively reviews the interconnect issue and mentions that the latency of the post-Moore's Law interconnects will exceed that of the transistors for interconnect lengths greater than 30 μm , which reveals an interconnect era beyond Moore's Law.

Integration of electrical and optical circuitry exhibits a promising solution for the interconnect issue. Development of optical interconnect network layers on Si CMOS circuitry offers a platform that fulfills the specific design requirements in terms of speed, power and bandwidth for chip-to-chip and also on-chip communication.

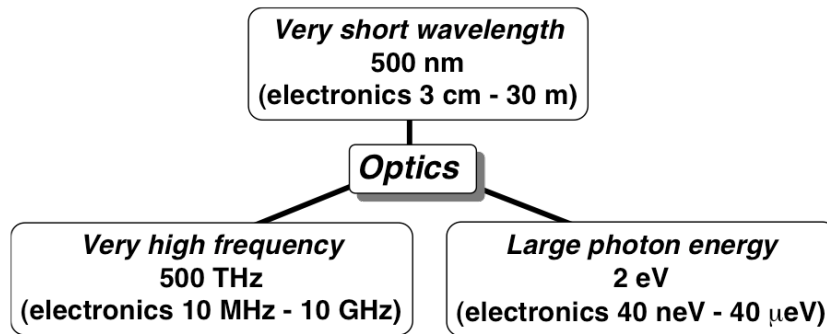


Figure 1.1 Differences between optics and electronics expressed in terms of wavelength, frequency and photon energy (After Ref. [4])

Figure 1.1 represents the substantial differences between optics and electronics in terms of wavelength, frequency and photon energy. Short wavelength of light enables confinement of light into low-loss dielectric waveguides (*e.g.* optical fiber), which provides low-loss propagation and directional manipulation of light. Electrical interconnect materials are lossy especially for high frequency signals due to skin effect. However, the carrier frequency of light is significantly high compared to electrical signals and any other practicable modulation frequency, which avoids frequency dependent loss. For the case of electrical interconnects, frequency dependent signal loss and distortion are substantial, either the line is LC with loss dominated by the skin effect, or it is RC with bulk resistive loss [6]. Figure 1.2 represents the propagation of optical and electrical signals in terms of loss and velocity.

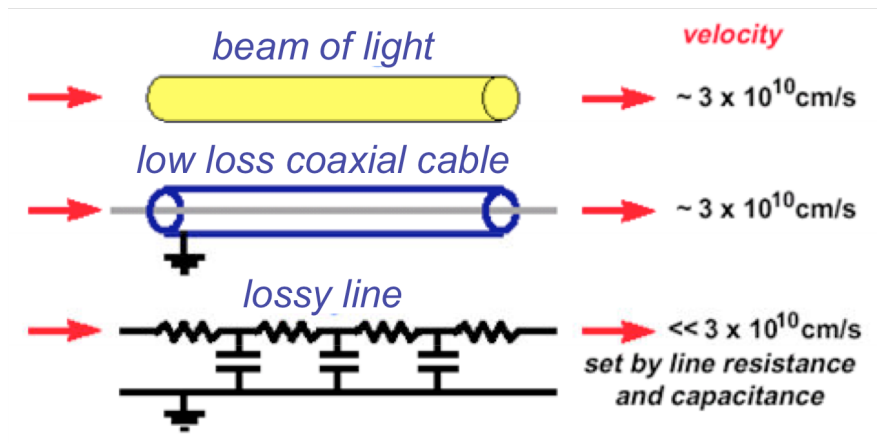


Figure 1.2 Optical and electrical propagation in terms of loss and velocity (After Ref. [4])

Above all, large photon energy of light enables perfect voltage isolation between different parts of circuits. Figure 1.3 shows an on-chip optical interconnect system that composed of a light source with an optical modulator (transmitter part) and photodetector (receiver part) with corresponding integrated electrical circuitry [7].

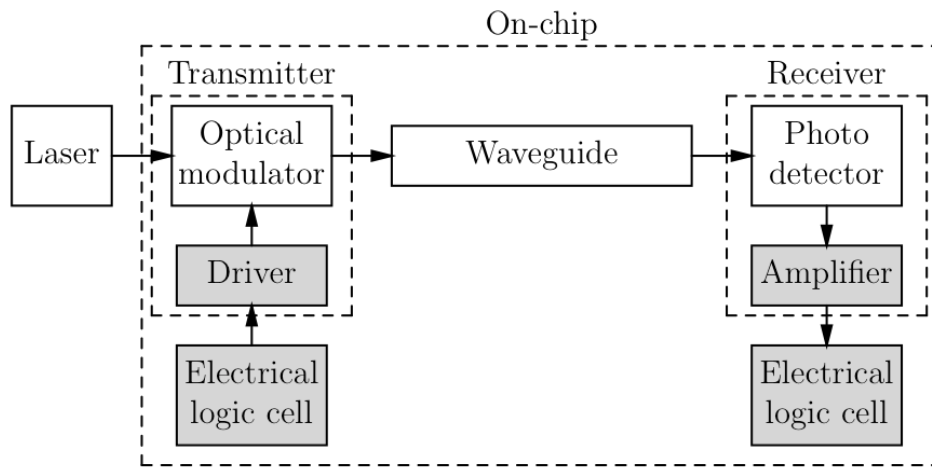


Figure 1.3 On-chip optical interconnection system (After Ref. [7])

Additionally, voltage isolation exists between two parts, because photons do not carry electrical information about the transmitter part by themselves. Indeed, photodetector generates electrical signal from the modulated and waveguide-coupled light at the receiver side and feeds into electrical circuitry that converts into digital output signal.

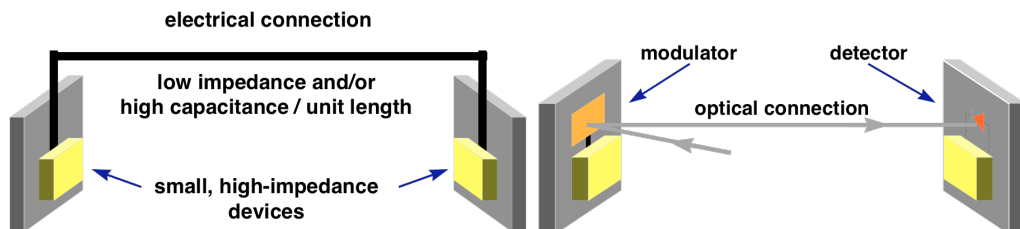


Figure 1.4 Electrical and optical interconnection system (After Ref. [4])

Large photon energy also enables quantum impedance conversion. Impedance transformers are needed for a classical electrical interconnect which

is composed of a low-impedance electrical connection line with high-impedance devices. Optical devices match the optical signal to the electrical circuitry with the aid of the quantum detection and generation. Figure 1.4 shows the impedance matching for a classical electrical and optical interconnection system. Miller presents further essential and comprehensive research review and historical summary of the development of optical interconnects and physical reasons for the integration of optics with the Si CMOS circuitry based on solving the mentioned issues [4-5].

1.2 Motivation

Development of optoelectronic devices and growth technologies based on enabling the integration of optical and electrical circuitry becomes crucial due to the communication bottlenecks that arise from the defined physical restrictions of electrical interconnects. Established Si CMOS technology provides a low cost platform and reproducible processing for on-chip optical and electronic signal processing. A wide number of materials and processes are also available for optical device and interconnect fabrication, however, monolithic integration with Si CMOS microelectronics is the basic concern [7]. Optoelectronic device technology, based on group III-V compounds and especially InGaAs, offers increased functionality and high performance. As a result, the detectors based on these materials are the “state-of-the-art” optoelectronic devices for near-infrared (NIR) and especially fiber telecommunication bands (1.31-1.55 μm) detection applications [9-11]. This is due to, i) high tunability of direct band gap energy [12], ii) low dark current achievement using lattice matched materials [13]. Despite its advantages, high raw material costs and integration difficulty with the current Si CMOS technology [14-17] hampers the widespread growth of III-V interconnection technology. Furthermore, construction of optical interconnection architectures requires materials with monolithic integration ability with standard Si CMOS technology and absorption capability that overcomes silicon’s spectral limitation.

Germanium (Ge) shows great promise with high absorption coefficient for NIR telecommunication wavelength range (1.31-1.55 μm) thanks to its suitable energy band gap ($E_{g(\text{direct})} = 0.8 \text{ eV}$, $E_{g(\text{indirect})} = 0.66 \text{ eV}$). Silicon is blind and silica fibers have low absorption and scattering losses [18] for the wavelength range of interest. Good transport properties also make Ge an attractive candidate for NIR photodetection and modulation. Figure 1.5 shows the spectral efficiency of Ge which spans wider absorption range over Si ($E_{g(\text{indirect})} = 1.1 \text{ eV}$) including telecommunication standards wavelength spectra [19]. The potential of the monolithic integration of Ge with Si makes it an ideal candidate.

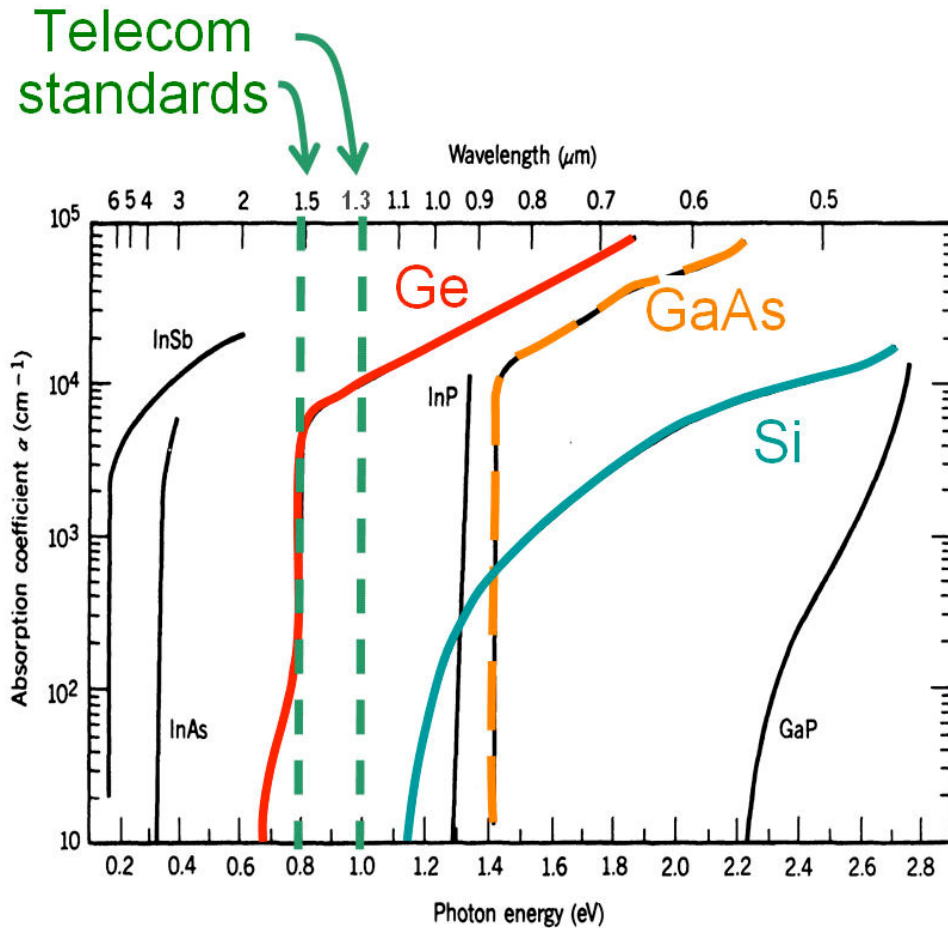


Figure 1.5 Absorption coefficient vs. Photon energy (and wavelength) for various semiconductors (After Ref. [19])

Table 1.1 and 1.2 shows the band gap energy and carrier mobilities of Si, Ge and III-V based compounds, respectively [20].

Crystal	Gap	E _g , eV	
		0 K	300 K
Si	i	1.17	1.11
Ge	i	0.744	0.66
InAs	d	0.43	0.36
GaAs	d	1.52	1.43

Table 1.1 Band gap energy of Si, Ge, InAs and GaAs at 0 K and 300 K
(i=indirect gap, d=direct gap) (After Ref. [20])

Crystal	Electrons	Holes
Si	1350	480
Ge	3600	1800
InAs	30000	450
GaAs	8000	300

Table 1.2 Carrier mobilities of Si, Ge, InAs and GaAs at room temperature, in cm²/V-s
(After Ref. [20])

High quality and defect-free heteroepitaxial growth of Ge on Si is a challenging process due to large lattice mismatch (4.2%) and results with islanding and misfit dislocations that are formed at the Si substrate and Ge film interface terminating at the film surface as threading dislocations [21]. To date, different research groups demonstrated high performance optoelectronic devices by using epitaxial techniques based on employing a low temperature buffer layer associated with cyclic thermal annealing [22-24] and epitaxial growth of compositionally graded Si_{1-x}Ge_x buffer layers [25-27] to reduce the threading dislocations.

Nayfeh *et al.* [21] concentrated on this issue by demonstrating a novel technique, multiple hydrogen annealing heteroepitaxy (*MHAH*), which enables the growth of high quality, low dislocation density and low surface roughness Ge films on Si [21], [28]. For this thesis work, material growth of high quality Si_xGe_{1-x} layers associated with the quantum-confined structures is performed based on this epitaxial growth technique.

1.3 Objectives

Previous research covers the demonstration of the growth of Ge on Si for high responsivity photodetectors [29-33] and high performance electro-absorption modulators [34-37] operating at telecommunication wavelengths. For development of alternative and promising approaches, objectives for this thesis are fabrication, material and device characterizations of SiGe based, integrated optoelectronic devices based on top-illuminated *p-i-n* architectures with grown $\text{Si}_x\text{Ge}_{1-x}$ multi quantum well (MQW) structures for demonstrating i) high responsivity and low dark current photodetectors, ii) high performance electro-absorption modulators exploiting quantum-confined Stark effect (QCSE).

1.4 Organization of the Thesis

This part of the chapter gives information about the progression of the thesis. Chapter 2 gives a review of operation principles of photodetectors and electro-absorption modulators offering a literature survey. Chapter 3 presents optoelectronic device fabrication of *p-i-n* layers composed of $\text{Si}_x\text{Ge}_{1-x}$ MQW structures. Chapter 4 discusses the material and device characterizations and analysis of *p-i-n* photodetector and electro-absorption modulator. Chapter 5 concludes the thesis with the conclusions and future suggestions.

Chapter 2

Optoelectronic Device Physics

This chapter provides a short overview on photodetection (specifically on *p-i-n* photodetectors) and optical modulation. Basic electro-absorption modulator operation is discussed with a sense of quantum-confinement concept based on quantum wells (QWs) and modulation mechanism of quantum-confined Stark effect (QCSE). This chapter further describes important performance parameters of photodetector and modulators. This chapter also offers a detailed review of recent literature on SiGe near-infrared photodetection and modulation.

2.1 Photodetector Overview

Semiconductor photodetector (photodiode) is essentially a *p-n* junction diode that converts incident optical radiation into electrical current. An incident photon with energy greater than the energy band gap of the semiconductor excites an electron to an upper energy level (conduction band) and leaves a hole (lack of electron) behind (valence band). The wavelength of the photon that carries an energy equal to the band gap energy is given as

$$\lambda = \frac{hc}{E_g} \approx \frac{1.24}{E_g} \quad (2.1)$$

where λ : wavelength (μm), h : Planck constant ($\text{eV}\cdot\text{s}$), c : velocity of light ($\text{m}\cdot\text{s}^{-1}$) and E_g : band gap energy (eV)

Figure 2.1 illustrates the absorption of a photon resulting in electron-hole generation in a semiconductor [38]. Applied (or built-in) electric field enables the collection of this optically generated electron-hole pair (ehp) by drift process through the material. Moving ehp's constitute photocurrent. Photons with energies higher than the band gap of the semiconductor contribute to the induced

photocurrent. This optical absorption process could be direct or indirect. Absorption of a photon requires a simultaneous momentum change (usually by a phonon) in indirect semiconductors (*e.g.* Si and Ge). Phonons are not involved for direct gap optical transitions.

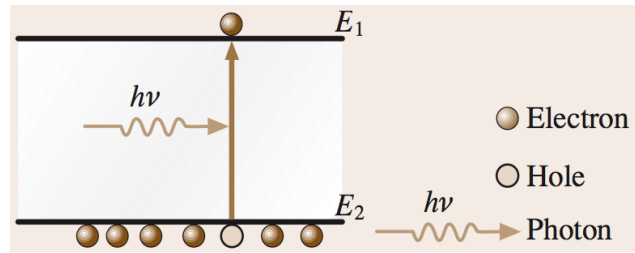


Figure 2.1 Electron-hole photogeneration in a semiconductor (After Ref. [38])

Various photodetector structures (*p-i-n*, MSM, APD) exist with characteristic advantages, however this overview mainly concentrates on *p-i-n* photodetectors.

2.1.1 *p-i-n* Photodetector

A *p-i-n* photodetector consists of an intrinsic (undoped) region sandwiched between highly doped *p*-type and *n*-type regions with corresponding ohmic contacts. Figure 2.2 a) illustrates a typical *p-i-n* photodetector structure. A conventional *p-n* junction diode, with highly doped *p*-type and *n*-type regions, results with a quite thin depletion region, which implies relatively high junction capacitance. Moreover, carriers generated in the *p*-type and *n*-type regions can contribute to the photocurrent only by diffusing into the depletion region, otherwise they recombine in the doped regions [39]. The presence of a thick intrinsic region (typical *p-i-n* photodetector) allows the absorption of more photons resulting in a higher photocurrent. Wider depletion region, effectively spanning the intrinsic region, results in low device capacitance. This enables high-speed photodetection and increased bandwidth because of decreased *RC*-related delays (assuming *RC*-limited, not transit time limited). Constant electric field across depletion region ensures collection of the photogenerated

carriers by drift process. The main challenge for a $p-i-n$ photodetector is the demand for high quality material growth techniques and application of multi-step fabrication processes. Figure 2.2 b) depicts the corresponding band diagram, charge and electric field distribution across a conventional $p-i-n$ device [12].

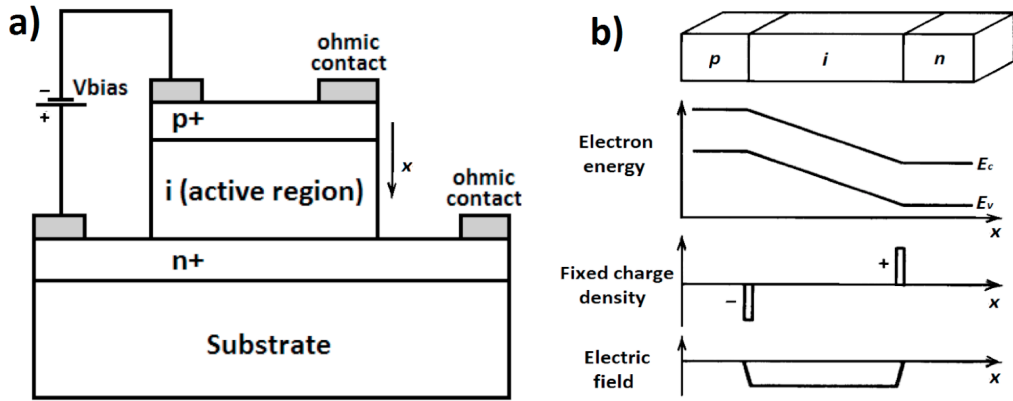


Figure 2.2 a) Top illuminated $p-i-n$ photodetector structure, b) Corresponding band diagram, charge and electric field distribution (After Ref. [12])

2.1.2 $p-i-n$ Photodetector Characteristics

Certain general metrics are used to evaluate the performance of photodetectors. Internal and external quantum efficiency, responsivity and bandwidth are extensively utilized for typical applications.

2.1.2.1 Current-Voltage ($I-V$) Characteristics

Typically $p-i-n$ photodetectors are operated at reverse bias condition. Reverse leakage current associated with thermal generation and recombination of carriers in the depletion region corresponds to the dark current. Under reverse bias condition, diffusion current is negligible due to a high potential barrier and the thermally generated carriers determine the current (drift current). Under forward bias condition, diffusion of carriers determines the current and increase exponentially with the applied voltage. Total current in a $p-i-n$ photodetector

(under no illumination) is the sum of diffusion and generation current and denoted by [41]:

$$I = qA \left(\frac{D_p}{L_p} p_n + \frac{D_n}{L_n} n_p \right) (e^{qV/kT} - 1) = I_0 (e^{qV/kT} - 1) \quad (2.2)$$

where D_n, D_p : diffusion coefficient for electrons and holes ($\text{cm}^2 \cdot \text{s}^{-1}$)

L_n, L_p : electron and hole diffusion length (cm)

p_n, n_p : equilibrium concentration of holes in n-type material and electrons in p-type material (cm^{-3})

I_0 : reverse saturation current (A)

A : active device area (cm^2)

In response to illumination with photons $h\nu > E_g$, where $h\nu$ corresponds to the photon energy with the specified frequency ($\nu = c/\lambda$), carriers are generated optically at a rate of g_{op} . Photogenerated ehp's in the depletion region and within a diffusion length of the transition region make-up the photocurrent (I_p).

$$I_p = qAg_{op}(L_p + L_n + W) \quad (2.3)$$

where W : depletion layer thickness (cm)

Total current (I_T) across the device under illumination is the combination of eqns. (2.2) and (2.3):

$$I_T = qA \left(\frac{D_p}{L_p} p_n + \frac{D_n}{L_n} n_p \right) (e^{qV/kT} - 1) - qAg_{op}(L_p + L_n + W) \quad (2.4)$$

The photogenerated carriers are collected by drift process; and the minus sign in eqn. (2.4) is originating from the flow of photocurrent from n -type towards p -type region. Figure 2.3 is a schematic illustration of p - i - n photodetector operation under illumination [42].

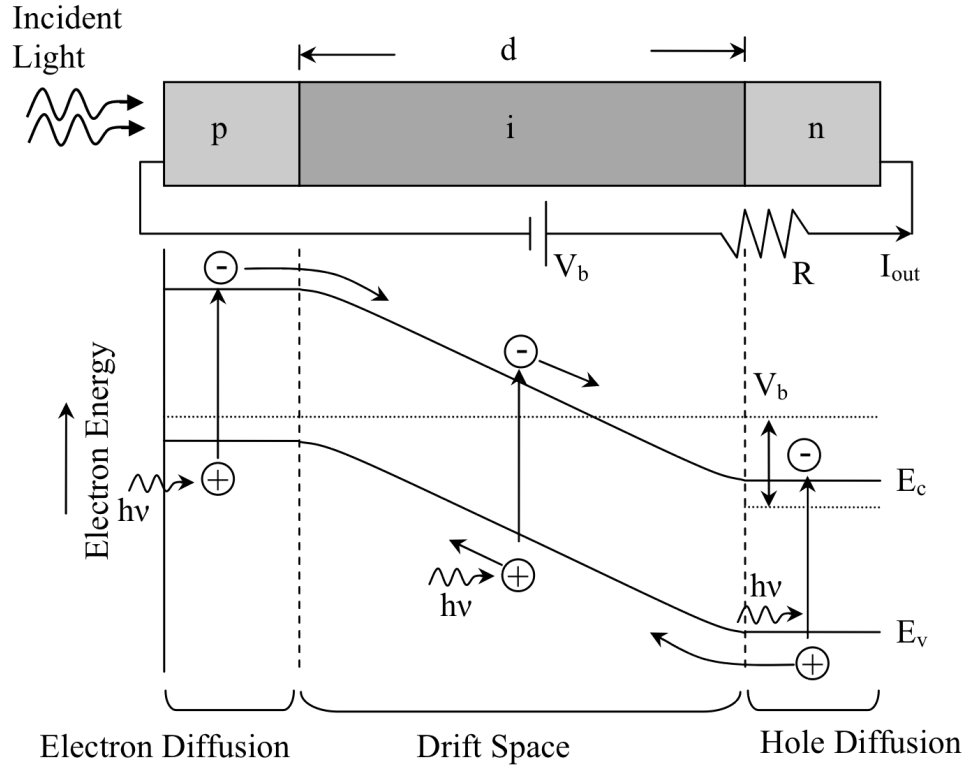


Figure 2.3 *p-i-n* photodetector operation under illumination (After Ref. [42])

2.1.2.2 Quantum Efficiency (η)

Internal quantum efficiency is a measure of the collection efficiency of photogenerated carriers. Typically internal quantum efficiency is above 90%, 10% loss attributed to recombination of small number of ehp's before being completely collected. External quantum efficiency, on the other hand, is a performance metric that relates the number of collected ehp's at the terminals to the incoming number of photons. External quantum efficiency (quantum efficiency) includes surface reflections, non-complete absorption of the incoming light (*e.g.* thin absorbing layers) in addition to internal quantum efficiency. Quantum efficiency ($0 \leq \eta \leq 1$) is defined as:

$$\eta(\lambda) = (1 - R)[1 - \exp(-\alpha(\lambda)d)] \quad (2.5)$$

where $\eta(\lambda)$: quantum efficiency, R : optical reflectivity of the surface, $\alpha(\lambda)$: absorption coefficient of the material (cm^{-1}), d : absorption layer thickness (cm)

The quantum efficiency is wavelength dependent since the absorption coefficient (α) of a semiconductor has also wavelength dependency. For $\lambda > \lambda_c$, where λ_c is the longest (cut-off) wavelength of absorption, η is very small (nearly zero) making the material transparent at those wavelengths (eqn. (2.1)). For very small λ (i.e. highly energetic photons), η is small since most of the photons are absorbed in a region very close to the material surface. Photogenerated carriers are usually recombined at G-R centers due to crystal imperfections at the surface before they can be extracted. An ideal *p-i-n* photodetector is expected to absorb all incident photons inside the depletion region and generate one electron per an incident photon that contributes to the photocurrent [39].

2.1.2.3 Responsivity ($\mathfrak{R}$)

Responsivity is a measure of the optical to electrical conversion efficiency of a photodetector. It is defined as the ratio of the generated photocurrent to the intensity of the incident optical power. It is directly related to the quantum efficiency through incoming photon energy as:

$$\mathfrak{R} = \frac{i_p}{P_{in}} = \frac{\eta e}{h\nu} = \eta \frac{\lambda}{1.24} \quad (2.6)$$

where $\mathfrak{R}$: responsivity (A/W), λ : wavelength (μm)

Responsivity has wavelength dependency as quantum efficiency. Responsivity and quantum efficiency defines the optical performance of an optoelectronic device.

2.2 Optical Modulator Overview

Optical modulation is defined as the manipulation of the properties of light (*e.g.* intensity, phase, polarization, etc.) in response to an external stimulus. In electro-absorption and electro-optic modulators the external stimulus is an

applied electric field (or voltage difference). Electro-absorption modulator operation is based on the electric field, $\mathbf{E}$, dependent absorption characteristics of the medium where the light beam is traveling. In electro-optic modulators, phase of the light is manipulated by changing the refractive index (n) of the material with an applied electric field.

Direct modulation of the light sources (*e.g.* lasers) is also possible by directly modulating the injected current. However, optical interconnect layers mentioned in Chapter 1 requires high-speed and low power modulation schemes. Electro-absorption modulators based on *p-i-n* MQW structures are attractive candidates that offer reverse bias operation (avoid injection of large number of carriers) and low capacitance; promising low power operation and high data rates.

2.2.1 Quantum Confinement

A quantum-confined structure “bounds” the motion of electrons (and holes) in one or more directions. Quantum wells (QWs) are two-dimensional (2D) structures that exhibit the principles of quantum confinement and allow the engineering of electronic states in a semiconductor. Quantization behavior of electron and hole states for potential well can be understood by solving Schrödinger’s equation:

$$-\frac{\hbar^2}{2m^*} \frac{d^2\psi(z)}{dz^2} + V\psi(z) = E\psi(z) \quad (2.7)$$

where V : potential barrier, m^* : effective mass and $\psi(z)$: electron (or hole) wave function

For the case of an infinite quantum well with a width of d , as shown in Figure 2.4 a) [38], there are allowed discrete energy states ($n=1,2,\dots$) within the well region. The solution for (2.7) is zero inside the barrier region since the barrier potentials are infinite. Normalized wave functions and energy states for the well region are:

$$\psi(z) = \sqrt{\frac{2}{d}} \sin\left(\frac{n\pi z}{d}\right) \quad (2.8)$$

$$E_n = \frac{\hbar^2}{2m_w^*} \left(\frac{n\pi}{d}\right)^2 \quad (2.9)$$

A more practical situation is illustrated, Figure 2.4 b) shows the confined energy states for a finite quantum well with barrier height of V_0 . Solution for eqn. (2.7) exists for both well and barrier regions due to the penetration of the wave functions into the barrier regions. Boundary conditions give a set of even and odd parity solutions that satisfy:

$$\tan\left(\frac{kd}{2}\right) = \frac{m_w^* \kappa}{m_b^* k} \quad (2.10)$$

$$\tan\left(\frac{kd}{2}\right) = -\frac{m_b^* k}{m_w^* \kappa} \quad (2.11)$$

where k is the wave vector in the well and κ is the exponential decay constant in the barrier and are given as:

$$\frac{\hbar^2 k^2}{2m_w^*} = E_n \quad (2.12)$$

$$\frac{\hbar^2 \kappa^2}{2m_b^*} = V_0 - E_n \quad (2.13)$$

Quantization of energy states and confinement of carriers in one dimension has important advantages. First of all, quantization nature shifts the effective band edge to a higher energy level and enables band-gap tunability without changing material composition. Furthermore, confinement of carriers in one dimension increases the probability for optical absorption (electron-hole generation) [38] due to the increased probability of finding an electron and hole in the same vicinity. Moreover, by special localization excitonic effects (electron-hole Coulomb interactions) become stronger hence further decrease

the optical absorption edge and exhibit a step-like increase in the absorption spectra due to the bound state of electron-hole pair. According to eqns. (2.9) and (2.12), confinement energy (E_n) is inversely proportional with the well width (d) and also with effective mass (m^*) which means that heavy and light-hole states have different energy levels.

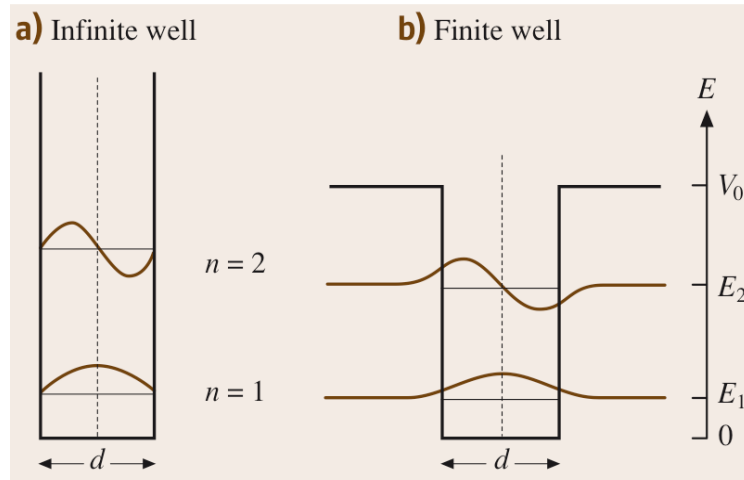


Figure 2.4 a) Quantum well with infinite barriers and confined energy states, b) Quantum well with finite barriers (V_0) and confined energy states (After Ref. [38])

2.2.2 Electro-absorption Effect

Electro-absorption effect is the change of the absorption coefficient of a medium in response to an external electric field ($\mathbf{E}$). An electro-absorption modulator operates based on changing the amount of absorbed light by electric field [39]. Franz-Keldysh Effect (FKE) and quantum-confined Stark effect (QCSE) are two main mechanisms that exhibit electro-absorption effect in semiconductors and both mechanisms provide operation near the band gap of semiconductors.

2.2.2.1 Franz-Keldysh Effect (FKE)

Franz-Keldysh Effect (FKE) is the electro-absorption mechanism observed in conventional bulk semiconductors. In response to an electric field ($\mathbf{E}$), energy bands are tilted as seen in Figure 2.5 and electron-hole wave functions penetrate into the band gap region. This increases the overlap of electron and hole wave

functions making it possible for the absorption of a photon with less energy than the band gap energy of the semiconductor ($E_g - dE$) [39]. Absorption of photons with ($E > E_g - dE$) becomes possible and results with a shift and broadening of the band edge absorption characteristics [40].

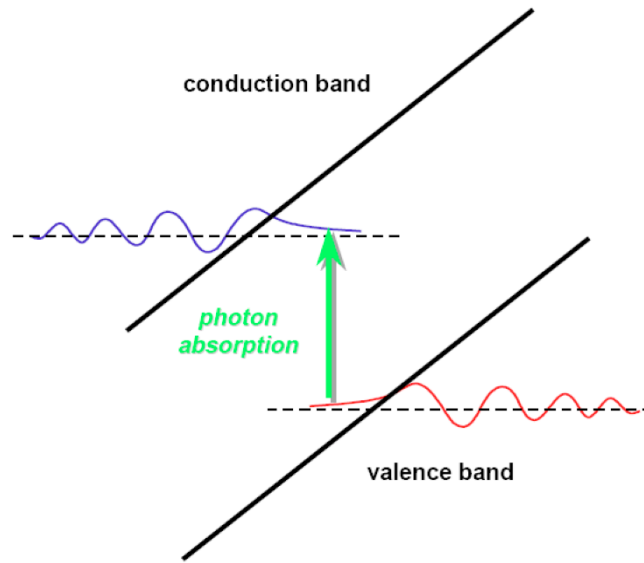


Figure 2.5 Schematic illustration of Franz-Keldysh effect (After Ref. [39])

Electric field dependency of the absorption coefficient is low for FKE (for especially telecommunication wavelengths). This can be understood if one considers the small probability to find an electron and a hole in close vicinity of each other in the real space. Additionally, strong excitonic effects play sovereign role in band edge absorption characteristics and these excitonic peaks broadens with the applied field due to field ionization. Electro-absorption modulators exploiting FKE have performance restrictions since high electric fields are needed to observe large absorption coefficient change ($\Delta\alpha$). FKE-based modulators, on the other hand, enjoy being low cost solutions due to the ease of growth and fabrication.

2.2.2.2 Quantum-Confined Stark Effect (QCSE)

Quantum-confined Stark Effect (QCSE) is the modulation of the energy levels of QWs in response to an applied electric field ($\mathbf{E}$) perpendicular to the plane of

the wells. QCSE is the quantized version of FKE. As shown in Figure 2.6 [39], electron and hole wave functions penetrate into “forbidden” regions and energy separation between lowest confined states ($\langle e1 | E | h1 \rangle$) are reduced with respect to that in the absence of external electric field ($E=0$). Hence, effective band gap (E_g) reduces in response to an applied electric field and absorption edge shifts to longer wavelengths (red shift). Since electron and hole states shift to opposite sides of the well, overlapping of electron and hole wave functions reduces and it results with the decrease of absorption coefficient and exciton absorption peak. As shown in Figure 2.7 [36], exciton absorption peaks are observed for especially low bias voltages for Ge/Si_xGe_{1-x} *p-i-n* MQW structures and broadening effect reduces since the walls of the wells prevent the exciton from field ionizing.

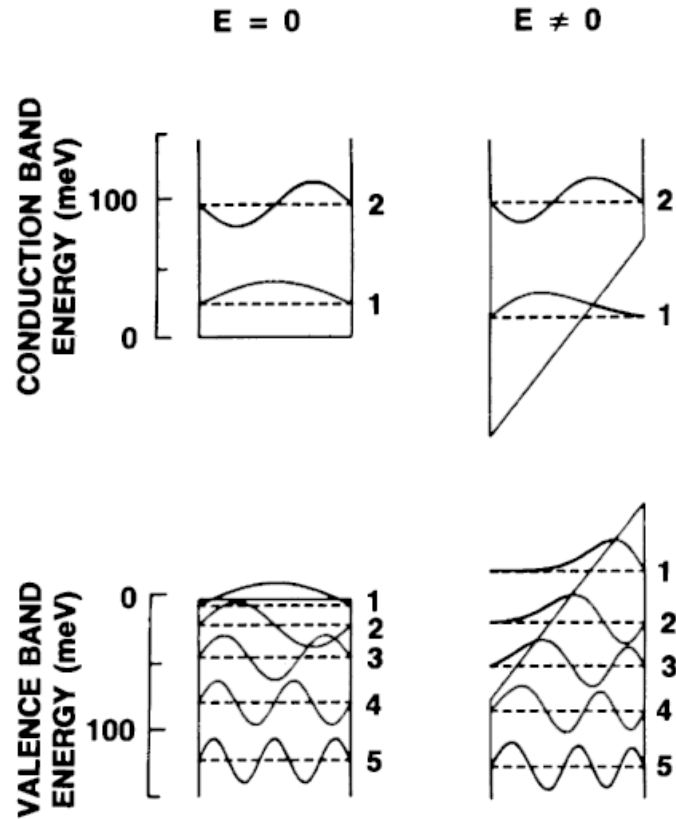


Figure 2.6 Schematic illustration of QCSE (After Ref. [39])

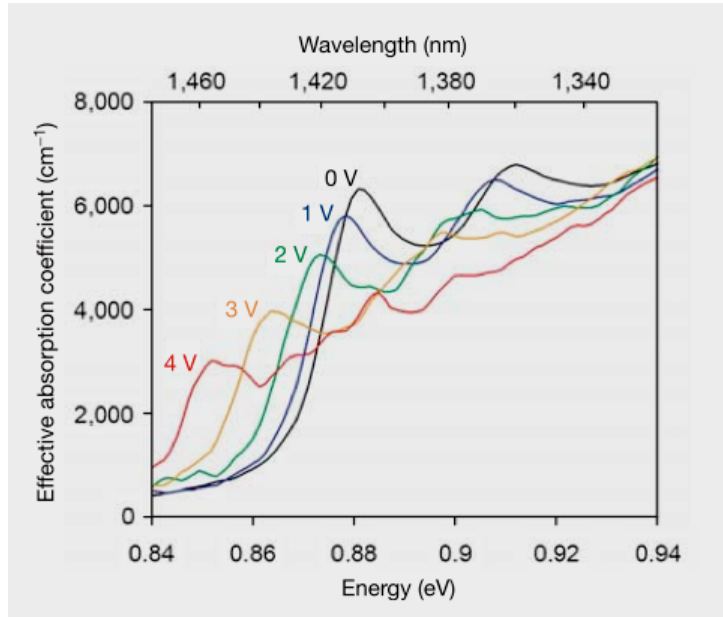


Figure 2.7 Electro-absorption spectra of *p-i-n* Ge/SiGe MQW structure exploiting QCSE (After Ref. [36])

QCSE has stronger electro-absorption behavior with respect to FKE with thanks to the quantum confinement nature. Excitonic effects are also obvious with respect to FKE, since electrons and holes are confined within the well region. Furthermore, the shape of the wells can be effectively modified with the electric field [38]. Consequently, large ΔE_g and $\Delta\alpha$ can be achieved with relatively low electric field with respect to FKE. The main expense comes from the requirement of controlled high quality growth and fabrication of *p-i-n* MQW architectures.

2.2.3 Electro-absorption Modulator Characteristics

An ideal electro-absorption modulator can be conceived as totally transparent to light (“optically on”) for zero bias ($E=0$) and absorbs all incident light (“optically off”) for particular electric field ($E \neq 0$). This section introduces performance metrics for an optical modulator such as contrast ratio, insertion loss and the comprised figure of merit as the performance parameters that should be considered in the design process of an electro-absorption modulator.

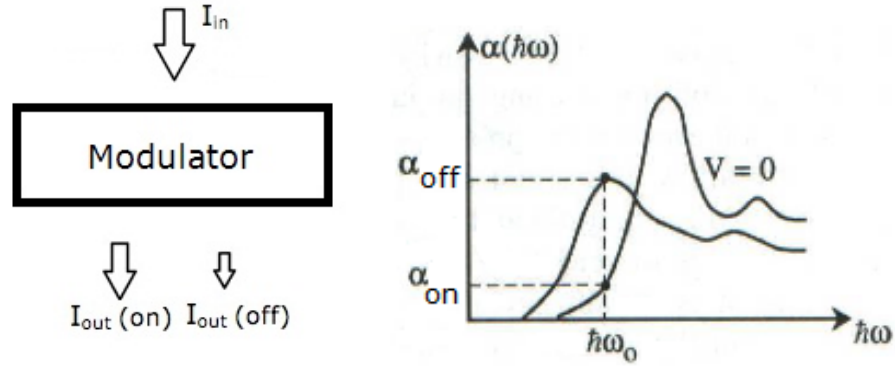


Figure 2.8 Electro-absorption modulator operation schematic representation

The light intensity between the input and output of the modulator can be related as:

$$I_{out(on,off)} = I_{in} (e^{-\alpha_{(on,off)} d_{eff}}) \quad (3.11)$$

where $\alpha_{on}, \alpha_{off}$: absorption coefficients for optically “on” and “off” states ($\alpha_{off} > \alpha_{on}$),
 d_{eff} : the thickness of MQW region

Contrast ratio (CR): CR is the ratio of the output intensity between optically “on” and “off” states for a particular electric field, **E**. Higher applied field implies larger absorption coefficient and less optical power appears at the output of the modulator at the “optically off” state.

$$CR = \frac{I_{out(on)}}{I_{out(off)}} = e^{(\alpha_{off} - \alpha_{on}) d_{eff}} \quad (3.12)$$

Modulation depth (MD): MD is the performance parameter that refers to the maximum change in absorption coefficient for particular wavelength and voltage swing.

$$MD = 1 - \frac{I_{out(off)}}{I_{out(on)}} = 1 - e^{-(\alpha_{off} - \alpha_{on}) d_{eff}} \quad (3.13)$$

Insertion loss (IL): Insertion loss corresponds to the ratio of the input light intensity to the output at optically “on” state. It is the performance parameter that represents the background material absorption, surface reflections and scattering losses through the modulator in optically “on” state.

$$IL = \frac{I_{in}}{I_{out}(on)} = e^{\alpha_{on}d_{eff}} \quad (3.14)$$

A figure of merit evaluating the optical performance of an electro-absorption modulator with the described performance parameters is defined as:

$$Figure\ of\ merit\ (FOM) = Contrast\ ratio\ (CR) / Insertion\ loss\ (IL) \quad (3.15)$$

For the design of a high performance modulator, FOM should be increased as much as possible. For the achievement of high FOM, absorption coefficient difference ($\Delta\alpha$) and ratio (α_{off}/α_{on}) for optically “off” and “on” states should be designed as large as possible. Moreover, absorption coefficient for transparent mode operation (α_{on}) should be minimized to achieve lower insertion loss.

2.3 SiGe Research Review

This part of the chapter discusses advances in the SiGe optoelectronic device technology summarizing the best-reported results for photodetectors and modulators.

2.3.1 *p-i-n* Photodetector Literature Review

In the SiGe technology, the main issue tackled in the recent literature is achieving high quality materials. SiGe optoelectronic device technology struggles with the threading dislocations that arise during the growth of epitaxial-Ge layer on Si due to 4.2% lattice mismatch. These threading

dislocations affect the carrier transport mechanisms and device parameters such as reducing carrier lifetime and mobility [43] and degrade the device performance in terms of increased dark current and reduced detection efficiency. To date, different research groups demonstrated several growth techniques to reduce the threading dislocations [22-27], as discussed in Chapter 1.

Dark current is a substantial device parameter that dictates the important factors such as power dissipation, signal to noise ratio and noise equivalent power. Low dark current levels are desired to become feasible alternatives to competing III-V based optoelectronic devices [44]. Table 2.1 is a list of the lowest-reported dark current performances and corresponding material growth techniques and other critical device parameters [26], [45-48].

Table 2.1			
Structure	Ge Thickness	Dark Current Density (A/cm ²)	Responsivity (A/W)
<i>p-i-n</i> Ge/Si	1.5 μ m	1.5×10^{-4}	0.13 @ 1.3 μ m
<i>p-i</i> Ge/ <i>n</i> Si	1 μ m	2×10^{-4}	0.01 @ 1.3 μ m
<i>p-i</i> Ge/ <i>n</i> Si	0.2 μ m	2×10^{-4}	0.02 @ 1.3 μ m
<i>p-i-n</i> Ge/Si	1 μ m	1×10^{-3}	0.2 @ 1.55 μ m
<i>n-i</i> Ge/ <i>p</i> Si	1 μ m	1×10^{-6}	<0.001 @ 1.3 μ m

Table 2.1 (cont'd)			
Structure	Growth Technique	Year	Ref.
<i>p-i-n</i> Ge/Si	Graded buffer UHVCVD	1998	[26]
<i>p-i</i> Ge/ <i>n</i> Si	LT/HT UHVCVD + annealing	2001	[45]
<i>p-i</i> Ge/ <i>n</i> Si	LT MBE	2004	[46]
<i>p-i-n</i> Ge/Si	LT/HT RPCVD + annealing	2007	[47]
<i>n-i</i> Ge/ <i>p</i> Si	LEPECVD + annealing	2008	[48]

Table 2.1 Reported best dark current performances associated with the growth techniques

Lowest dark current density (1×10^{-6} A/cm²) is achieved with *n-i* Ge/*p* Si configuration [48]. The growth of 1 μ m thick Ge epitaxial layer is performed with cyclic thermal annealing using low-energy plasma-enhanced chemical vapor deposition (LEPECVD) system. Cyclic thermal annealing associated with the LEPECVD growth reduces threading dislocation density significantly ($\sim 2 \times 10^7$ cm⁻²), hence reducing the dark current. Effect of annealing is obvious, since the same growth without annealing exhibits dark current density of $\sim 2 \times 10^{-3}$ A/cm². Acquired responsivity values are less than 1×10^{-3} A/W at 1.3 μ m due to the high potential barrier (for holes) between undoped Ge and

p-type Si layer, which reduces carrier collection efficiency. Low-temperature molecular beam epitaxy (LT MBE) growth of *p-i* Ge/*n* Si configuration exhibits slightly higher dark current density (2×10^{-4} A/cm²) with the responsivity of 2×10^{-2} A/W at 1.3 μ m [46]. Other growth techniques such as graded buffer UHCVD, LT/HT UHCVD and LT/HT RPCVD exhibit low dark current with higher detection efficiency performance [26], [45], [47].

Table 2.2 shows the best-reported SiGe based *p-i-n* and an extremely efficient MSM photodetector responsivity performances and corresponding parameters.

Table 2.2			
Structure	Ge Thickness	Responsivity (A/W)	Dark Current Density (A/cm ²)
<i>n-i</i> Ge/ <i>p</i> Si	4 μ m	0.89 @ 1.3 μ m	11×10^{-3} @ 0.5 V
<i>n-i</i> Ge/ <i>p</i> Si	4 μ m	0.75 @ 1.55 μ m	15×10^{-3} @ 1 V
<i>n-i</i> Ge/ <i>p</i> Si	1 μ m	1.08 @ 1.55 μ m	41×10^{-2} @ 0.5 V
<i>i</i> Ge/Si (MSM)	4.5 μ m	0.85 @ 1.55 μ m	100×10^{-3}

Table 2.2 (cont'd)			
Structure	Growth Technique	Year	Ref.
<i>n-i</i> Ge/ <i>p</i> Si	UHCVD + annealing	2002	[30]
<i>n-i</i> Ge/ <i>p</i> Si	UHCVD + annealing	2002	[30]
<i>n-i</i> Ge/ <i>p</i> Si	UHCVD + annealing	2007	[29]
<i>i</i> Ge/Si (MSM)	RPCVD + annealing	2006	[31]

Table 2.2 Reported best responsivity performances for different device structures

Highest responsivity for top illuminated *p-i-n* photodetector is reported [30] as 0.89 and 0.75 A/W at 1310 and 1550 nm, respectively. *n*-type and intrinsic Ge (~ 4 μ m) layers are grown by employing low temperature buffer layer and cyclic thermal annealing using UHCVD system. Thick intrinsic region is increased the carrier generation. The corresponding dark current densities are 11 and 15×10^{-3} A/cm² at 0.1 and 0.5 V, respectively. Low dark current exhibits low defect density layers. The integration of photodetectors with waveguides [29] exhibits increase in the detection efficiency. Higher dark current (41×10^{-2} A/cm² at 0.5 V) is due to large peripheral leakage in waveguide architecture, which dominates for small area devices. High responsivity (1.08 A/W at 1.55 μ m) is achieved with low fiber-waveguide coupling loss and waveguide propagation loss. Maximum achievable

responsivity is acquired with very low bias [30] (or zero bias [29]) condition, which proves that the built-in electric field across the intrinsic region is sufficient for carrier collection. Highest responsivity (0.85 A/W at 2 V) for a SiGe based MSM photodetector is reported by Okyay *et al.* [31]. The growth is based on the novel heteroepitaxy technique (*MHAH*), which enables low dislocation density heteroepitaxial growth of Ge on Si. Measured responsivity values are comparable with the demonstrated *p-i-n* devices [29-30]. Detailed growth information can be found in the Appendix section.

2.3.2 *p-i-n* Electro-absorption Modulator Literature Review

Electro-absorption modulator research review covers the best modulation performances based on the modulation mechanisms of Franz-Keldysh [49] and quantum-confined Stark effect [36], [50-51]. All of the configurations include reverse bias operated *p-i-n* devices associated with the $\text{Si}_x\text{Ge}_{1-x}$ alloy in the intrinsic region. Table 2.3 depicts the demonstrated electro-absorption modulators with the corresponding device and performance parameters.

Table 2.3		
Published by:	Kimerling's Group (Ref. [49])	Miller's Group (Ref. [36])
Year	2008	2005
Modulation Mechanism	Franz-Keldysh effect (FKE)	Quantum-confined Stark effect (QCSE)
Device Structure	<i>p-i-n</i> $\text{Si}_{0.08}\text{Ge}_{0.92}$	<i>p-i-n</i> $\text{Ge}/\text{Si}_{0.15}\text{Ge}_{0.85}$
Growth thickness	400 nm	10 pairs of (10nm Ge/16 nm $\text{Si}_{0.15}\text{Ge}_{0.85}$)
Contrast Ratio	10 dB @ 1540 nm @ 7 V	Peak contrast of 4.69 @ 1461 nm
Insertion Loss	3.7 dB @ 1550 nm	--
Operation Wavelength	1539 - 1553 nm	1443 - 1471 nm

Table 2.3 (cont'd)	
Published by:	Saraswat and Miller's Group (Ref. [50-51])
Year	2007
Modulation Mechanism	Quantum-confined Stark effect (QCSE)
Device Structure	<i>p-i-n</i> $\text{Ge}/\text{Si}_{0.16}\text{Ge}_{0.84}$
Growth thickness	10 pairs of (10nm Ge/33 nm $\text{Si}_{0.16}\text{Ge}_{0.84}$)
Contrast Ratio	>3 dB @ 1475 - 1497 nm @ 6 V
Insertion Loss	--
Operation Wavelength	1475 - 1497 nm

Table 2.3 Reported electro-absorption modulator performances based on FKE [49] and QCSE [36], [50-51]

Researchers at MIT reported a waveguide-integrated *p-i-n* $\text{Si}_{0.08}\text{Ge}_{0.92}$ structure as a high performance electro-absorption modulator exploiting FKE [49]. The design is optimized for C-band telecommunication range

(1530-1565 nm) with the appropriate material composition. Growth is performed with UHVCVD system with cyclic thermal annealing. Silicon waveguides are utilized for light propagation and butt-coupling into and out of *p-i-n* device. Absorption for wavelengths longer than 1540 nm is enhanced with the applied field. Contrast ratio of 10 dB at 1540 nm and 7 V bias, insertion loss of 3.7 dB at 1550 nm is achieved. Modulation depth is increased significantly (85% at 7 V) with the applied voltage higher than 4 V.

A *p-i-n* device associated with 10 pairs of MQWs (10 nm Ge/16 nm Si_{0.15}Ge_{0.85}) in the intrinsic region exploiting QCSE is demonstrated by research groups at Stanford University [36]. Growth is performed with RPCVD system with intermediate thermal annealing steps. This work is the very first demonstration of a SiGe MQW electro-absorption modulator with the modulation performance comparable to that of conventional III-V based devices. Electro-absorption operation wavelength is between 1443-1471 nm and further reported for 1550 nm operation at higher temperatures [37]. 4.69 of absorption coefficient ratio ($\alpha_{off} / \alpha_{on}$) is achieved at 1461 nm operation.

In 2007, Stanford researchers demonstrated an optical link employing Ge/SiGe MQWs [50-51]. A photodetector and a modulator with 10 nm Ge and 33 nm Si_{0.16}Ge_{0.84} MQW pairs are connected with SiGe waveguides. The growth is based on RPCVD growth followed by cyclic thermal annealing to reduce the threading dislocation density. QCSE is exploited with a contrast ratio >3 dB for 1475 – 1497 nm wavelength range and 6 V bias. Photodetectors show responsivity up to 0.26 A/W. This work implies a proof-of-concept demonstration for the integration of photodetectors and modulators to build an optical interconnect.

All of these approaches are promising demonstrations for small footprint, low power and high-speed operation. Furthermore, high electro-absorption performance and Si CMOS compatibility opens a path for integration of electrical and optical circuitry.

Chapter 3

Device Fabrication

The epitaxial layers composed of $\text{Si}_x\text{Ge}_{1-x}$ MQW structures were grown using Multiple Hydrogen Annealing for Heteroepitaxy (*MHAH*) [21] technique at Stanford Nanofabrication Facilities (SNF). All of the remaining device fabrication processes are conducted in class 100 and class 1000 facilities at UCF (UNAM clean room facilities) and ARL (Advanced Research Laboratories) at Bilkent University. This chapter details processing steps that are performed for the fabrication of *p-i-n* photodetector and electro-absorption modulator. Details of layer growth are provided in the Appendix section.

3.1 Substrate and Surface Preparation

MHAH-grown 4" Silicon p-type wafers are cleaved into small pieces and fabrication is performed on sample pieces. Piece processing reduces the yield however, is preferred in this work due to limited supply of epi-grown-wafers. Epi-grown-wafers are labeled as *I18* and *I19*. Nanostructural characterization information (layer thicknesses, material composition, etc.) is given in Chapter 4.

Surface preparation before device fabrication is critical for performance and repeatability. Although the starting substrates are Si, the Ge-rich layers are not compatible with standard RCA cleans. SC-1 and SC-2 cleans attack Ge layers. Therefore, samples are first ultrasonically degreased in acetone ($(\text{CH}_3)_2\text{CO}$), isopropyl alcohol ($(\text{CH}_3)_2\text{CHOH}$) and methanol (CH_3OH). Samples are then rinsed in de-ionized (DI) water and dried by a nitrogen gun. Following the removal of organic contaminants by the previous steps, hydrofluoric acid (HF) cyclic cleaning is performed. Samples are treated in dilute HF ($\text{HF}(40\%):\text{H}_2\text{O}=1:50$) solution and DI water consecutively and repeated for

several times. This clean ensures ultra-clean surface and removes any native oxide layer.

3.2 Patterning

Photolithography process is used to transfer the desired patterns onto the substrate. A photo mask is designed using LayoutEditor (GNU GPL) tool [50]. The mask writing is performed with a Heidelberg Instruments DWL-66 Mask Writer in UCF. A three-mask process is designed with an initial mask layer used to define circular mesa shapes of $p-i-n$ devices with 20 μm to 150 μm diameters. After deposition of a dielectric layer, consequent alignment steps are used to define contact windows in dielectric layer and a final mask to form top and bottom metal electrodes. Test structures for SEM imaging and alignment marks are also included in the designed photomask. Figure 3.1 shows the mask with Chromium (Cr) patterns and the designed patterns in CAD environment.

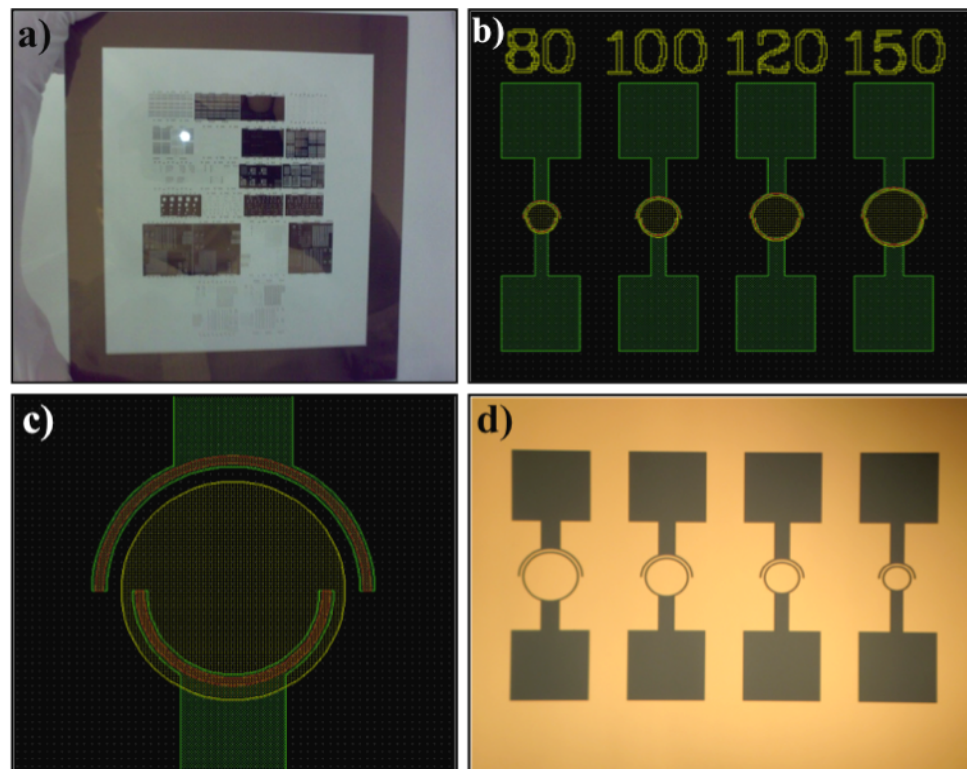


Figure 3.1 a) Photolithography mask, b) Multi-level CAD design of $p-i-n$ structures, c) Multi-level design (closer view), d) Optical micrograph image of metallization lift-off mask

Surface de-hydration of samples is performed on a hot plate at 110°C for 5 min. This step removes humidity off the surface, ensuring better and repeatable photoresist coverage as well as improving the resolution of the features. Hexametyldisilazane (HMDS) layer is used to promote photoresist adhesion on the surface. AZ5214E of AZ Electronic Materials photoresist (PR) is spin-coated at 5000 rpm for 50 seconds resulting in 1.3- μm -thick layer. Pre-exposure bake is used to remove solvents in the photoresist. Electronic Vision Group EVG620 Mask Aligner is used for alignment and UV exposure with constant dose (~ 50 mJ) at all photolithography steps. Post-exposure bake can be used to further improve resolution, but this step was usually skipped, as the minimum feature size in this work was repeatable without this step. AZ400K developer (AZ400K:H₂O=1:4) is used for the development of the exposed samples.

3.3 Dry Etching

Dry etching is performed for the definition of *p-i-n* circular mesa structures using Ultra High Vacuum (UHV) Reactive Ion Etcher (RIE) in ARL. Process development prior to etching process is performed to acquire etch rates for Si, Ge, Si_xGe_{1-x} and photoresist. Acquiring accurate etch rates are crucial for *p-i-n* device fabrications since it is critical to etch down to *p*-type layer, so the mesa structure contains all *n*-type, intrinsic and *p*-type layers successively from top to bottom. PR is used as masking layer and SF₆ is used as the process gas. Etch profiles are inspected with DEKTAK stylus profilometer, ZYGO Newview7200 optical profilometer and SEM imaging to ensure the consistency of the projected etch depth and mesa geometry. Figure 3.2 a) shows a top view of an etched sample, each circle corresponding to mesa shapes with different diameters. The planar scanning distance is set prior to measurement. Figure 3.2 b) depicts the schematic representation of the etched sample and c) shows the surface profile with ZYGO optical profilometer. Measured etch depths are ~ 400 and ~ 500 nm, for samples *II8* and *II9*, respectively.

3.4 Dielectric Film Coating

Dielectric film quality is immensely important for the photodetector fabrication since it is used both as anti-reflection (AR) coating and for electrical surface passivation. High film quality is required for low surface leakage. Besides, conformal deposition of the dielectric material around the mesa shape is crucial for *p-i-n* mesa structures to make sure that each layer are electrically isolated from each other prior to metallization process in addition to suppress sidewall leakage.

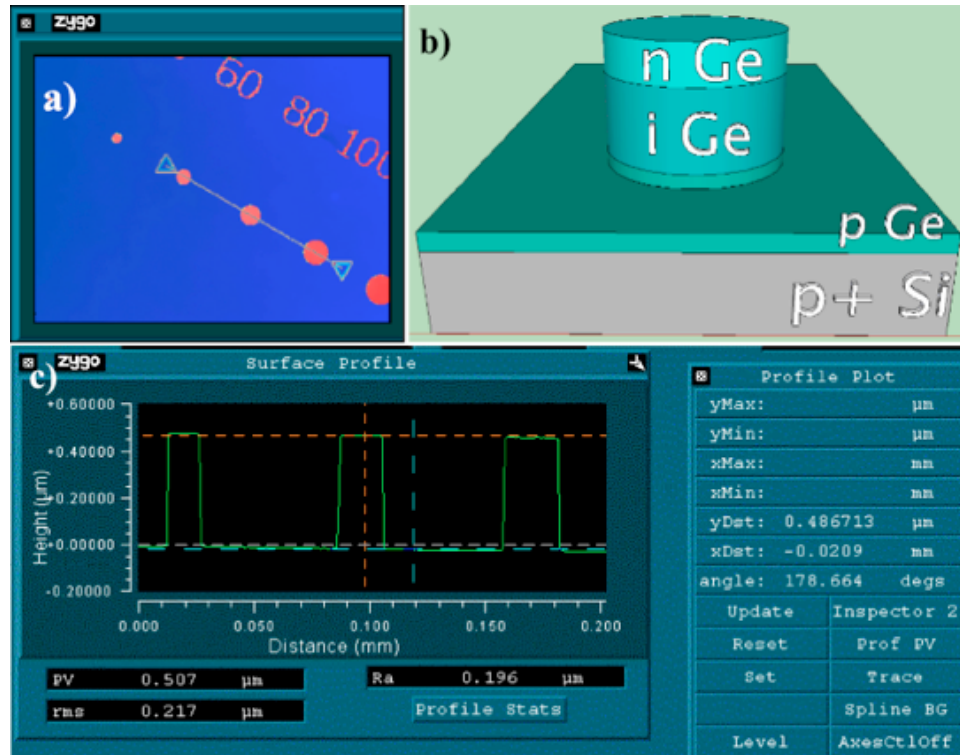


Figure 3.2 a) Top view of the circular mesa structures on ZYGO optical profilometer program, b) Schematic 3D representation of one of the etched samples, c) Scan results of ZYGO optical profilometer

Conformal deposition of high quality and low stress Si_xN_y is performed using Plasma Enhanced Chemical Vapor Deposition (PECVD) system. SiH_4 (200 sccm) and NH_3 (4 sccm) are used as process gases and He (50 sccm) is used for low stress film deposition. Process development is performed prior to deposition. Process temperature is set to 250°C with the chamber pressure of

1 Torr and RF power of 9W. Deposition rate is calculated as 9.3 nm/min and the thicknesses of the deposited Si_xN_y films (~ 100 nm) are confirmed with J. A. Woolam V-VASE Ellipsometer.

3.5 Wet Etching

Wet etching is used to form via holes through the Si_xN_y layer in order to contact p - and n -type layers. Si_xN_y is etched using buffered HF solution ($\text{HF}(40\%):\text{NH}_4\text{F}(40\%)=1:7$) and PR is used as masking layer. Process development is performed prior to etching using test samples. Figure 3.3 a) shows the optical micrograph image and b) shows the schematic representation of the etched sample.

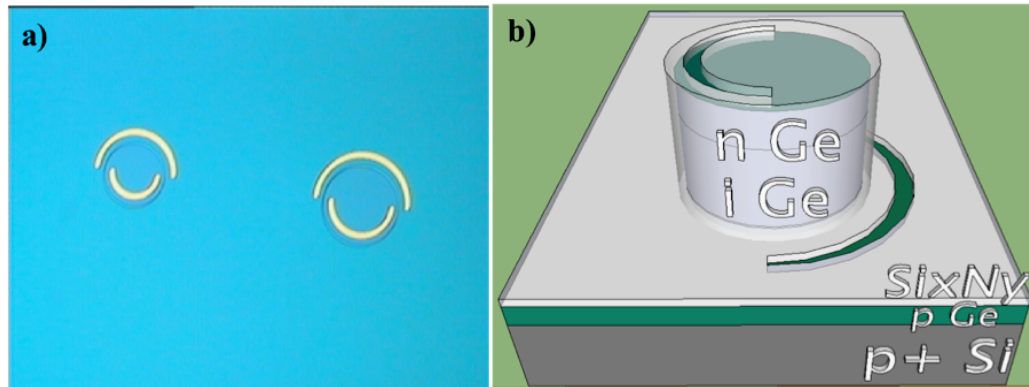


Figure 3.3 a) Optical micrograph image (top view), b) Schematic representation of the etched sample

3.6 Metallization and Electrode Formation

Fabrication of the p - i - n photodetector structures is completed with metallization and the definition of top and bottom (n - and p -type layers, respectively) electrodes. After the last alignment photolithography, an “HF-last” step is performed to ensure oxide free surface. 200-nm-thick aluminum (Al) is evaporated by VAKSIS thermal evaporator with an ultra-thin (~ 10 nm) layer of Titanium (Ti) in between to enhance the adhesion of Al onto the sample surface. Samples are rotated during evaporation to enable conformal sidewall coverage

and also uniform deposition on sample surface. After metallization, samples are left in acetone for lift-off process. Figure 3.4 shows the schematic representation, SEM and optical micrograph image of the final $p-i-n$ mesa structure.

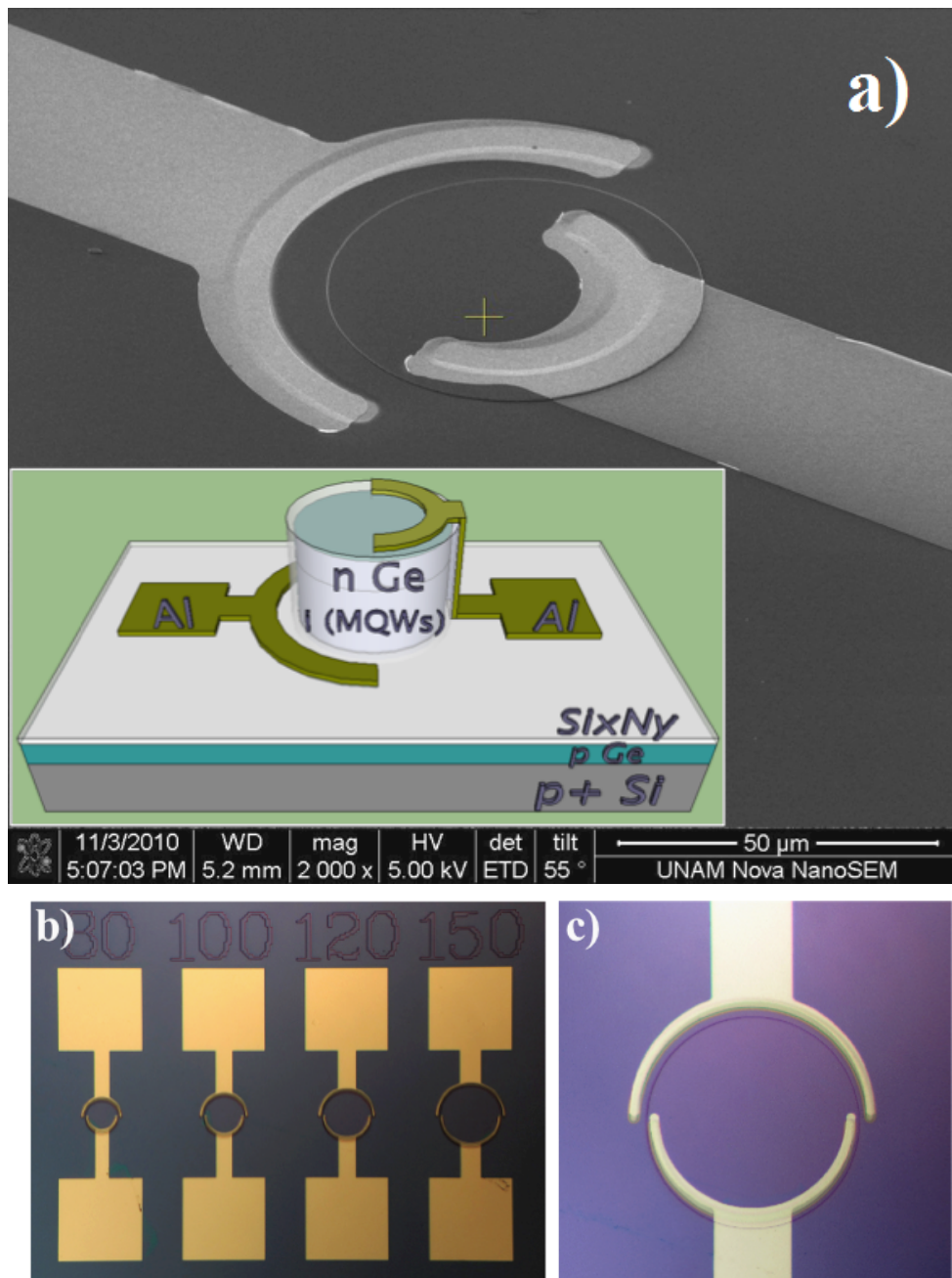


Figure 3.4 a) SEM micrograph image of final $p-i-n$ device and schematic representation (inset), b) Optical micrograph image of devices with different MESA diameters, c) Optical micrograph image of one of the devices

Chapter 4

Material and Device Characterization

This chapter describes the nanostructural material characterization of grown two different *p-i-n* Si_xGe_{1-x} MQW architectures (labeled as *II8* and *II9*) and optoelectronic device characterization of the fabricated devices. Material characterization includes Transmission Electron Microscopy (TEM), X-ray photoelectron spectroscopy (XPS), Photoluminescence (PL) and Raman spectroscopy measurements to acquire material compositional information and ensure the quality of grown layers. Band structures of the grown samples are revealed with the acquired characterization data. Device characterization involves electrical and optical characterization for the demonstration of photodetector and electro-absorption modulator operation.

4.1 Material Characterization

Material growth of the *p-i-n* MQW structures is performed using a novel heteroepitaxy technique, Multiple Hydrogen Annealing for Heteroepitaxy (*MHAH*). Growth of the layers used in this thesis is a topic of another study. The details of the growth process can be found in the appendix section. This section presents the nanostructural characterization studies and results obtained.

4.1.1 Nanostructural Characterization

Cross-sectional Transmission Electron Microscopy (TEM) is used to determine the crystal quality of the grown layers in addition to the thickness of alternating well and barrier regions. Figure 4.1 shows TEM images of the grown quantum structures. Epitaxial growth with low defect and threading dislocation density is obtained. Furthermore, strained MQW pairs can be smoothly distinguished with high contrast imaging. Layer thicknesses are extracted from TEM images and are listed in Table 4.1.

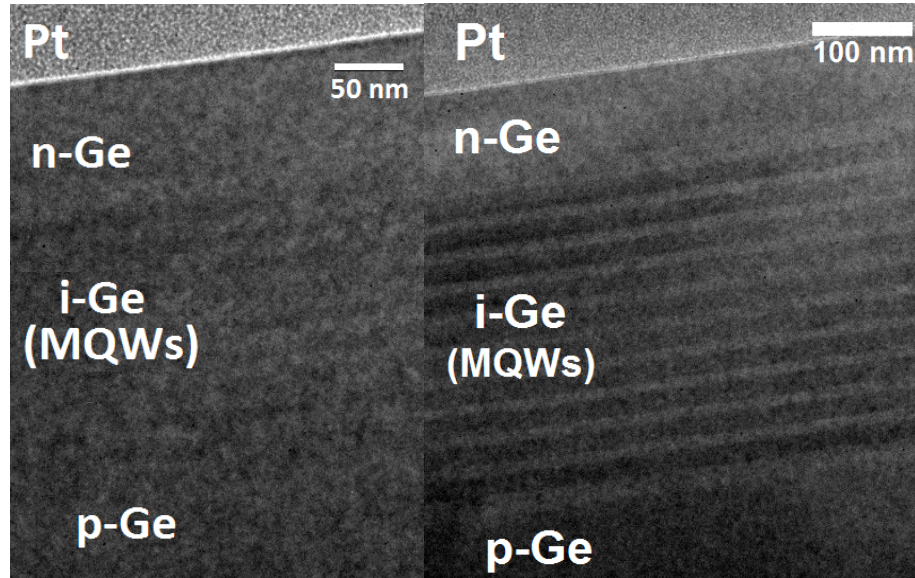


Figure 4.1 TEM images of *p-i-n* MQW structures (samples *I18* and *I19*, respectively)

<i>p-i-n</i> MQW architectures (10 MQW pairs)		
	I18	I19
layers	~layer thicknesses (nm)	
<i>n</i> -type Ge	100	100
intrinsic (Ge MQWs)	200	300
Ge well (each)	5	10
Si _x Ge _{1-x} barrier (each)	15	20
<i>p</i> -type Ge	370	370

Table 4.1 Layer thicknesses of *p-i-n* MQW structures (samples *I18* and *I19*)

X-Ray photoelectron spectroscopy (XPS) measures the binding energies of atoms and acquires composition related information about the grown layers. Layer thicknesses of *p-i-n* and MQW layers with the material compositional information is essential to reveal the heterostructure band diagram and analyze the optoelectronic device operation.

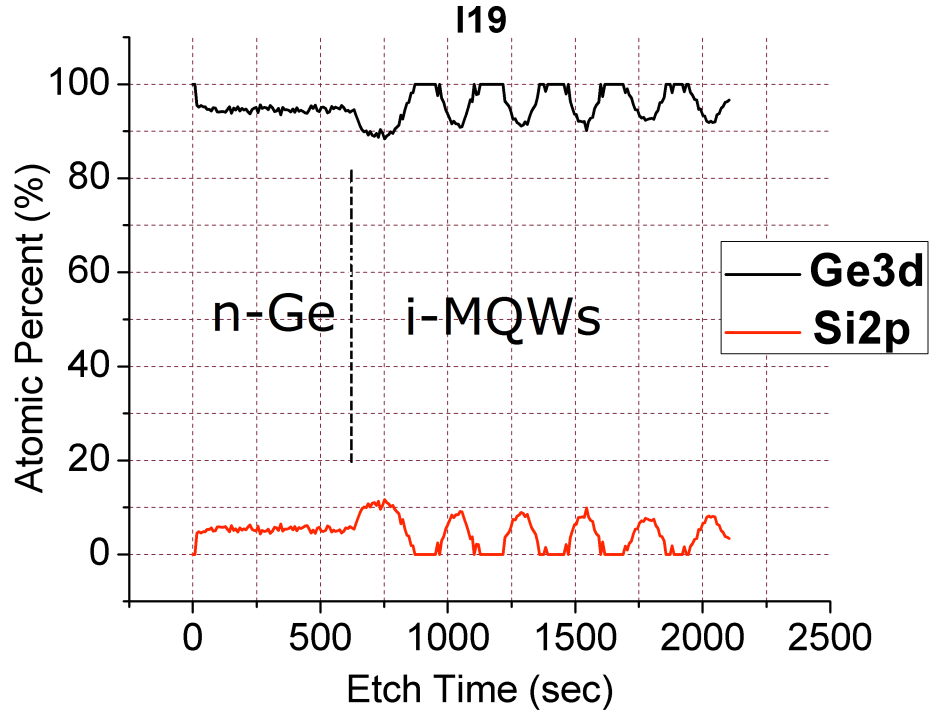


Figure 4.2 XPS Study - Concentration profile in terms of depth (sample I19)

The XPS analysis of the layers for Si (Si-2p) and Ge (Ge-3d) binding energies were carried out. The layers are in-situ etched by a secondary beam and scattered energy spectrum is recorded periodically. Samples are etched with a rate of ~ 0.2 nm/sec and scattered spectrum is recorded at the end of each 8-second interval, as shown in Figure 4.2. The undulating behavior of Si and Ge concentration proceeding from $t=600$ sec, is due to concentration modulation between barrier ($\text{Si}_x\text{Ge}_{1-x}$, $x=0.1$) and well (Ge) regions. By direct linear interpolation of direct gap between Si and Ge, *n*-type Ge cap layer ($\text{Si}_{0.05}\text{Ge}_{0.95}$) has an absorption edge which is shorter than 1550 nm (excluding weak indirect gap absorption). Hence, provides near-transparent behavior around 1550 nm operation range.

Photoluminescence (PL) spectrum is measured to observe the crystalline quality of *p-i-n* MQW structures and probe available energy states and allowed transitions between the states. PL measurements were obtained by light

excitation at $\lambda = 225$ nm. The layers have the sharp luminescence peaks at 425 nm and 500 nm, as shown in Figure 4.3. Electroluminescence (EL) measurement is also recorded, however emission peak is not observed attributed to the indirect gap of Ge and thick intrinsic region.

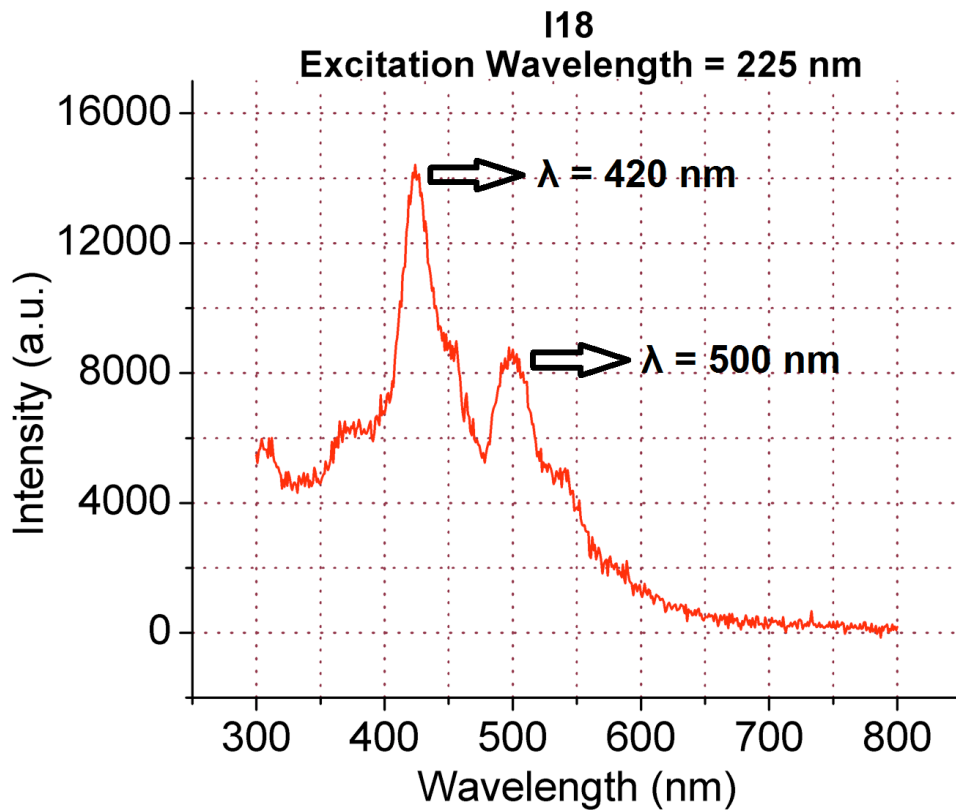


Figure 4.3 Photoluminescence spectra with excitation wavelength of 225 nm (sample I18)

Raman spectroscopy is performed to investigate phonon modes of the system. Typical Raman spectrum of a $\text{Ge}/\text{Si}_x\text{Ge}_{1-x}$ system might involve Ge-Ge, Ge-Si and Si-Si vibrational modes and depend on the film thickness, stress, material content and quality [52]. The shifted energy of excitation photons of 532 nm gives information about the material composition as shown in Figure 4.4. The penetration depth of such excitation enables us to get information about the Ge and $\text{Si}_x\text{Ge}_{1-x}$ ($x=0.1$) layers. Ge-Ge peak (~ 297) corresponds to the Raman shift associated with Ge-rich layers. Furthermore, Si-Ge (~ 385) and Si-Si (~ 450) peaks represent the Si-Ge and Si-Si bonds of $\text{Si}_x\text{Ge}_{1-x}$ layers. Peak

positions are highly consistent with the linear fit equations acquired with compositional analysis of $\text{Si}_x\text{Ge}_{1-x}$ layers from the literature [53]. Note that, (Si-Si) Raman shift peak of bulk Si is not observed due to poor penetration.

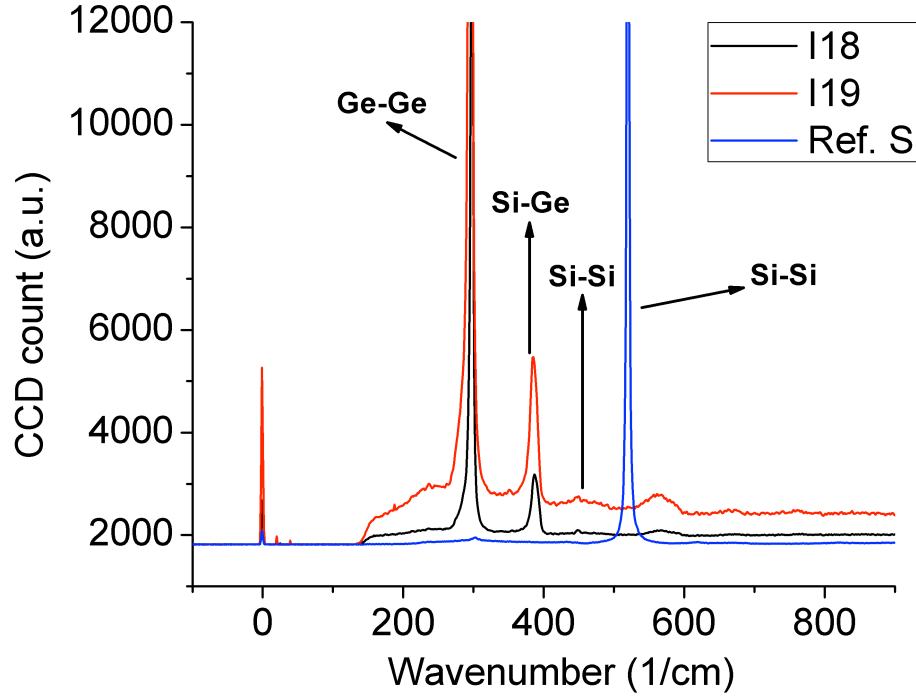


Figure 4.4 Raman spectroscopy (sample I18, I19 and ref. Si wafer)

4.1.2 MQW Band Structure

Band structure parameters such as well and barrier band gaps ($E_g(\text{Ge})$, $E_g(\text{Si}_x\text{Ge}_{1-x})$) and band offsets ($\Delta E_{c\Gamma}$, $\Delta E_{v,hh}$, $\Delta E_{v,lh}$) are important to predict photodetector and electro-absorption modulator operation. Acquired layer thicknesses and material compositional information are employed to calculate MQW band alignments. Note that, global conduction band minima of Ge and Si (L and Δ valleys, respectively) correspond to different momentum with respect to valence band global maxima. Hence, indirect gap optical efficiency (e.g. optical detection and emission) of Ge is low. Additionally, Ge-rich $\text{Si}_x\text{Ge}_{1-x}$ ($x=0.1$) barrier regions will exhibit “Ge-like” optical properties with global conduction minima at L-valleys. Accordingly, band alignments for both well (Ge) and barrier ($\text{Si}_x\text{Ge}_{1-x}$, $x=0.1$) regions are calculated for the direct

gap optical absorption (at the zone center, Γ). Figure 4.5 shows the band structure of Ge/Si_xGe_{1-x} ($x=0.1$) MQWs [54].

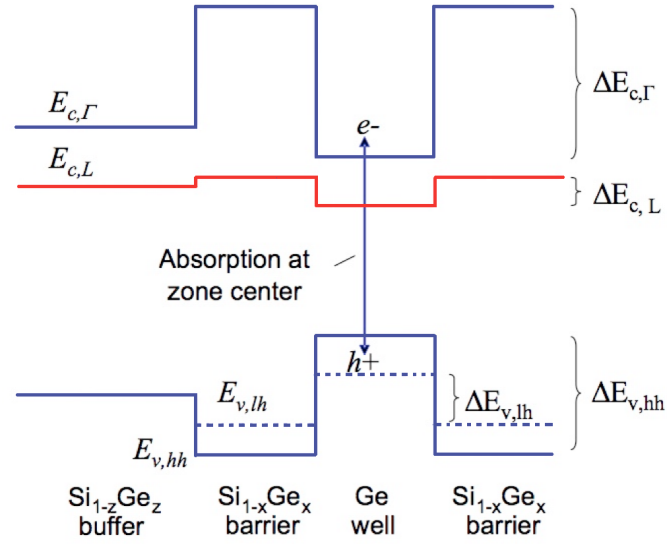


Figure 4.5 Ge/Si_xGe_{1-x} MQW band structure (After Ref. [54])

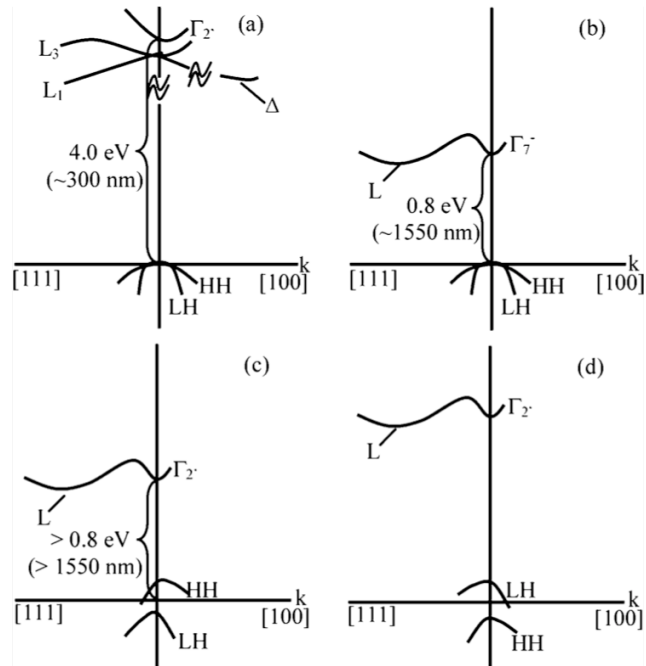


Figure 4.6 Band structures of a) Si, b) Ge, c) compressive strained Ge and d) tensile strained Ge-rich Si_xGe_{1-x} (After Ref. [37])

Note that, heavy-hole (hh) and light-hole (lh) band edges are split due to the compressive strain (for well region) and tensile strain (for barrier region) along the MQW region. Figure 4.6 [37] depicts the band structures for a) Si, b) Ge, c) compressive strained Ge and d) tensile strained Ge-rich $\text{Si}_x\text{Ge}_{1-x}$. Herein, Galdin *et al.* predicted the conduction and valence band offsets for strained $\text{Si}_{1-x}\text{Ge}_x$ layers on relaxed $\text{Si}_{1-z}\text{Ge}_z$ as reported in [55]. Heavy hole and light hole valence band offsets ($\Delta E_{v,hh}$ and $\Delta E_{v,lh}$) for $|x - z| < 0.5$ and $z > 0.5$ are given as:

$$\Delta E_{v,hh}(x,z) = (0.74 - 0.07z)(x - z) \quad (4.1)$$

$$\begin{aligned} \Delta E_{v,lh} = & -0.3z + 0.289z^2 - 0.142z^3 + (0.683 - 2.58z + 3.21z^2 - 1.24z^3)x + \\ & (0.435 + 0.704z - 2.439z^2 + 1.295z^3)x^2 + \\ & \frac{(-0.354 - 3.77z + 8.79z^2 - 2.46z^3)}{(1 - 2.7z + 28.1z^2)}x^3 \quad (4.2) \end{aligned}$$

Calculated band offsets for samples *II8* and *II9* and the effective masses give information about the confined energy states in the well region. Note that, $\Delta E_{c,\Gamma}$ is extracted from the difference of $E_g(\text{Si}_x\text{Ge}_{1-x})$ and $(E_g(\text{Ge}) + \Delta E_{v,hh})$. Further, $E_g(\text{Si}_x\text{Ge}_{1-x})$ is predicted by linear interpolation between $E_g(\text{Si})$ (~ 4.0 eV) and $E_g(\text{Ge})$ (~ 0.8 eV) at the zone center, Γ . The effective masses for $\text{Si}_{1-x}\text{Ge}_x$ at the zone center are also linearly interpolated between the values of Si and Ge and given as [56-57]:

$$m_e = 0.041m_o + 0.115(1 - x)m_o \quad [56] \quad (4.3)$$

$$m_{hh} = 0.28m_o + 0.21(1 - x)m_o \quad [57] \quad (4.4)$$

$$m_{lh} = 0.044m_o + 0.116(1 - x)m_o \quad [57] \quad (4.5)$$

where m_o is the free electron mass (9.11×10^{-31} kg)

Table 4.2 shows the calculated band parameters associated with the electron and heavy-hole energy levels for the samples *II8* and *II9*.

Band Parameters and Energy Levels		
Samples	I18	I19
Well	Ge	Ge
Barrier	Si _{0.1} Ge _{0.9}	Si _{0.1} Ge _{0.9}
Well thickness	5 nm	10 nm
Barrier thickness	15 nm	20 nm
$\Delta E_{c\Gamma}$	253 meV	253 meV
$\Delta E_{v,hh}$	67 meV	67 meV
$\Delta E_{v,lh}$	30 meV	30 meV
E_c (e1)	108 meV	47 meV
E_c (e2)	--	173 meV
E_v (hh1)	21 meV	8 meV
E_v (hh2)	65 meV	63 meV

Table 4.2 Band parameters and electron, heavy-hole energy levels (samples I18 and I19)

4.2 Device Optoelectronic Characterization

4.2.1 Current-Voltage (I - V)

Device characterization of the fabricated p - i - n MQW samples begins with current-voltage (I - V) measurements. Dark current measurements are performed under no illumination condition using Agilent B1500A semiconductor parameter analyzer and probe station with micrometer driven manipulators. Illuminated current measurements are performed under commercial solar simulator (with AM1.5G filter) illumination.

4.2.1.1 Dark Current

I - V characterization of fabricated samples is started with dark current measurements to analyze the electrical performance of the devices and ensure that the p - i - n devices are operational. Figure 4.7 shows the I - V (dark current) curve of one of the fabricated devices of sample I18.

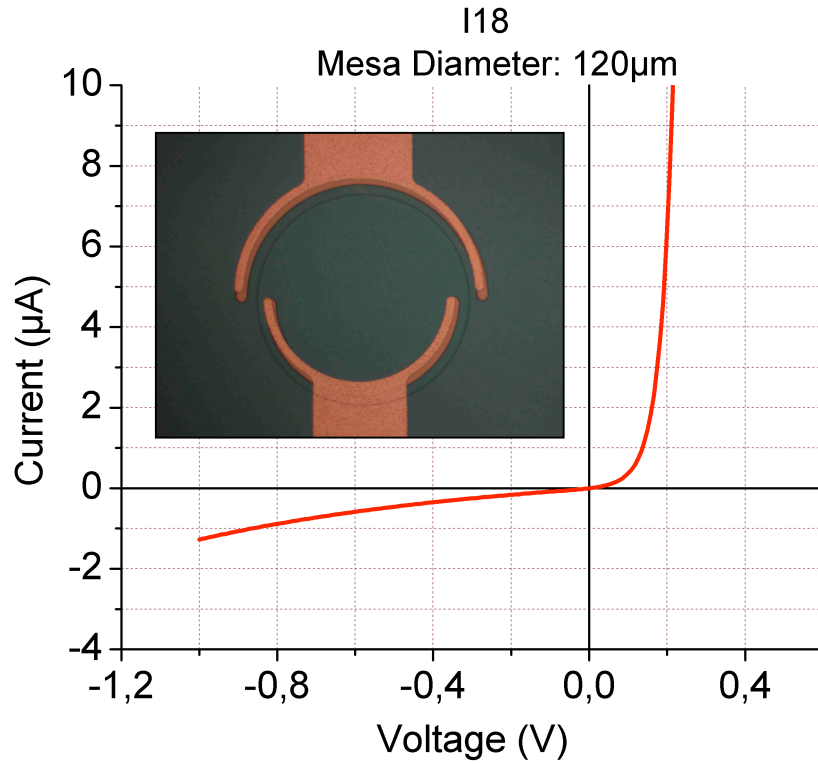


Figure 4.7 Current-Voltage (I - V) characteristics (sample *I18*)

Fabricated devices are operated under reverse bias for photodetection mode operation and exhibit low reverse leakage current. Reverse leakage currents of ~ 10 and ~ 5 mA/cm² are recorded at -1 V for *I18* and *I19*, respectively. These values are comparable with the lowest reported values for *p-i-n* photodetectors in the literature [45-47]. Figure 4.8 shows the dark current with respect to mesa area at different reverse bias voltages. Linear relation between leakage current and mesa area indicates that the bulk leakage dominates over surface leakage and the bulk component essentially determines total leakage. Thus, it reveals the quality of surface passivation along the mesa sidewalls.

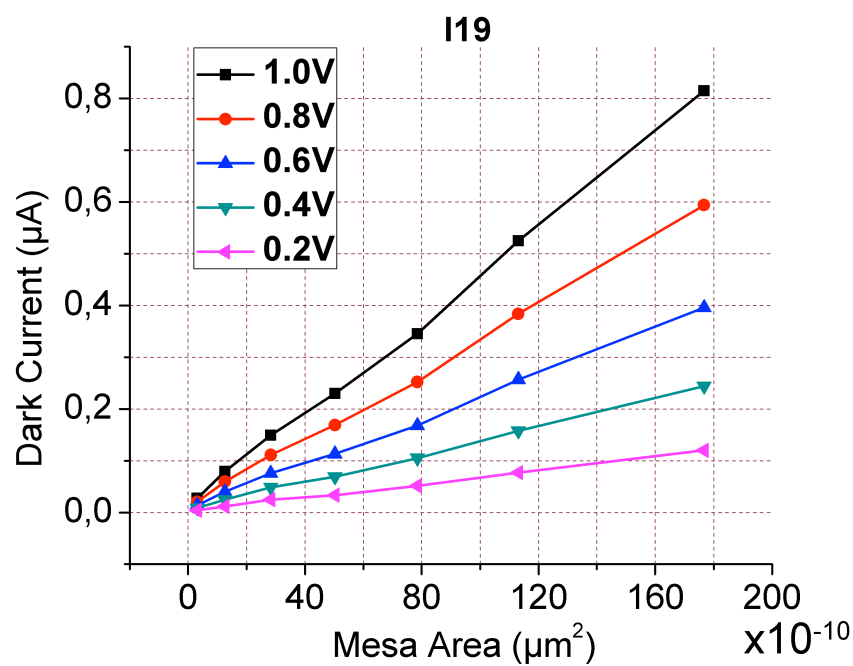
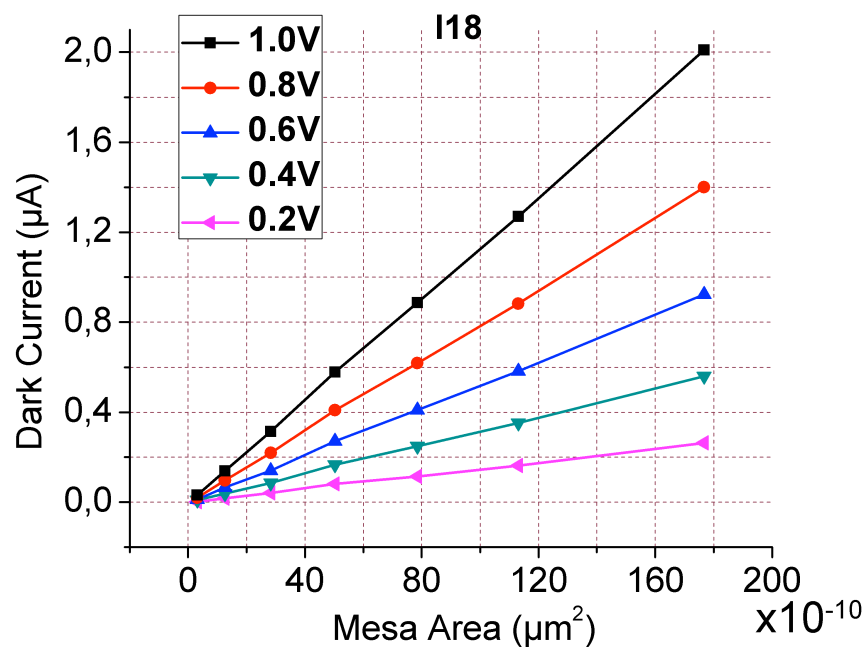


Figure 4.8 Dark current vs. Mesa area at different bias voltages
(samples *I18* and *I19*, respectively)

4.2.1.2 Illuminated Current (AM1.5G)

Although the layer thicknesses of MQW regions of the samples are not optimized for solar cell applications, I - V response under AM1.5G solar simulator illumination is recorded as shown in Figure 4.9.

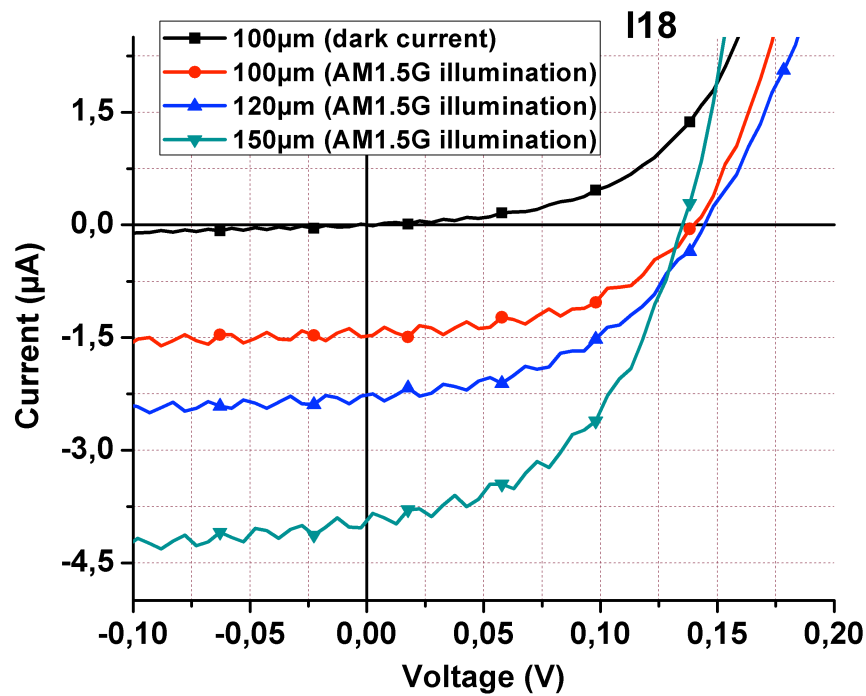


Figure 4.9 Dark & Illuminated (AM1.5G) I - V characteristics (sample *I18*)

Solar Simulator (AM1.5G)				
Mesa Diameter (μm)	I_{sc} (μA)	V_{oc} (mV)	P_{max} (nW)	Fill factor (FF)
100	1.48	140	102	0.48716216
120	2.26	144	156	0.4800885
150	3.9	135	256	0.48581197

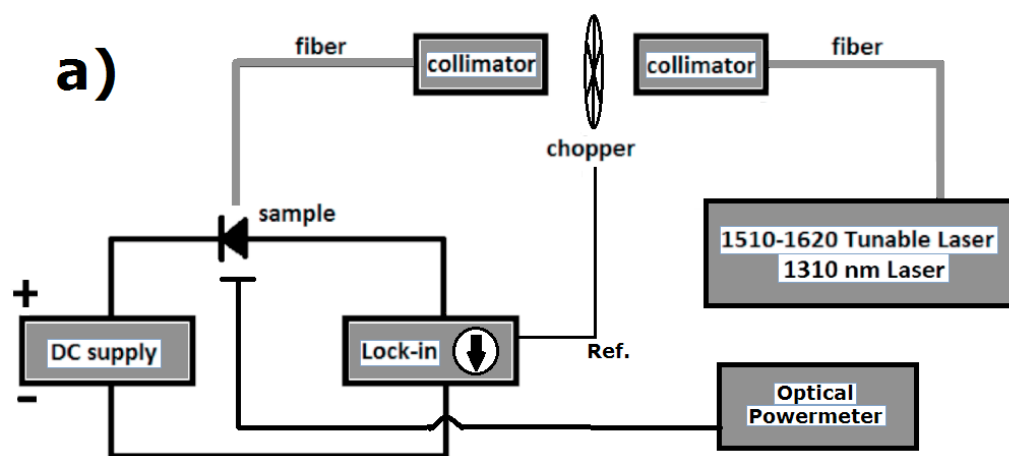
Table 4.3 I_{sc} , V_{oc} and P_{max} and Fill factor for various mesa diameters (sample *I18*)

Short-circuit current (I_{sc}) and open-circuit voltage (V_{oc}) with respect to the mesa diameter are shown in Table 4.3. Since the devices can be treated as parallel-connected current sources with increasing mesa diameter, I_{sc} is increased linearly with increased mesa area. On the other hand, mesa diameter

dependency of V_{oc} is negligible, as expected. Calculated power conversion efficiency ($P_{out(max)}/P_{inc}$) is around $\sim 1\%$ and P_{inc} is calculated by linear scaling of area of solar simulator output beam to the active device area. Power conversion efficiency is low compared to the conventional Si solar cell architectures [58] since the $p-i-n$ structures that comprises $\sim 200-300$ nm of intrinsic region are optimized for photodetection and modulation operation at the telecommunication wavelength range. The CMOS compatibility of $p-i-n$ MQW structures renders them as promising on-chip power sources for applications in self-powered CMOS integrated MEMS and sensing devices.

4.2.2 Responsivity ($\mathfrak{R}$) and Quantum Efficiency (η)

Responsivity (and quantum efficiency) measurements are performed to reveal optical detection and modulation performances of the fabricated $p-i-n$ MQW samples. 1310 nm (single wavelength) and 1510-1620 nm (tunable wavelength) coherent fiber coupled laser sources are used to demonstrate the optoelectronic device operation. $p-i-n$ devices are operated in reverse bias condition and incident light is aligned onto the device with single mode fiber using micrometer driven XYZ stage. Fiber core diameter (9 μm) is selected to be smaller than the area of the devices (20-150 μm), for better coupling of incident light. Light is modulated with an optical chopper with the modulation frequency of ~ 330 Hz and photocurrent data is acquired with standard lock-in technique using a Stanford Research Systems SR830 lock-in amplifier. Each measurement is taken by aligning the optical fiber initially followed by fine-tuning of the coupling from the fiber to the detector by monitoring photocurrent. Optical power of the incident light is measured using optical powermeter with a calibrated InGaAs photodetector and used in responsivity calculation. Note that, this calculation could slightly underestimate the actual responsivity since we assume all of measured optical intensity is coupled into the detector. Figure 4.10 a) shows schematic representation and photograph of the b) general view of optical characterization set-up, c) light modulation part and d) fiber-to-detector coupling part.



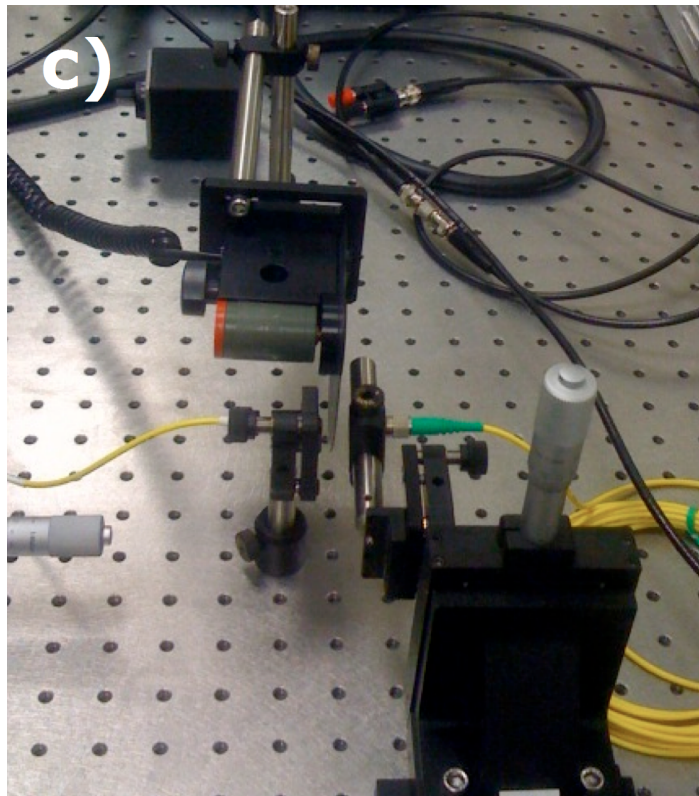


Figure 4.10 a) Schematic representation of optical characterization set-up and photograph of the
 b) general view of the set-up, c) light modulation part and d) fiber-to-detector coupling part

4.2.2.1 Photodetector Characterization (@1310 nm)

Optoelectronic device characterization of the fabricated *p-i-n* MQW samples is initiated with the illumination at 1310 nm to observe the photodetector operation. Table 4.4 shows the characterization data with the measured photocurrent and calculated responsivity, quantum efficiency and effective absorption coefficient values.

Wavelength=1310nm (Mesa Diameter=100μm)				
Sample	Photocurrent (nA)	Responsivity (A/W)	Quantum Efficiency	Abs. Coef. (cm ⁻¹)
I18	488	0.29	27%	19500
I19	548	0.33	31%	15270

Table 4.4 Optical characterization data at 1310 nm and 0 V (samples I18 and I19)

Acquired photocurrent and calculated responsivity at 1310 nm is observed to be bias independent for both samples and implies that the built-in voltage across the intrinsic MQW region is sufficient for effective collection of photo-generated carriers. Furthermore, high quantum efficiency (27 and 31%) and low power operation associated with the thin absorption region (300-400 nm) verifies good film quality of grown layers. Absorption coefficient values are calculated from the acquired responsivity data by combining eqns. (2.5) and (2.6) correcting for the reflectivity of Si_xN_y anti-reflection (AR) coating (*R*):

$$\alpha(\lambda) = -\frac{1}{d} \ln\left(1 - \frac{\Re(\lambda)}{\lambda} \frac{1.24}{(1-R)}\right) \quad (4.6)$$

Note that, absorption coefficients are calculated based on the total thickness of MQW region. Bias independent absorption shows that the devices are outside of the electro-absorption operational wavelength range. Fabricated samples are power efficient candidates for the detector part of an optical interconnect system, since the maximum achievable responsivity is reached at zero bias condition.

4.2.2.2 Optical Modulator Characterization (@1510-1620 nm)

Electro-absorption properties of the fabricated samples are investigated with the same optical characterization set-up shown in Figure 4.10. A tunable laser source (1510-1620 nm) is used to sweep the wavelength of incident radiation. Figure 4.11 shows the optical characterization data of sample *I18* (5 nm Ge/15 nm Si_{0.1}Ge_{0.9}).

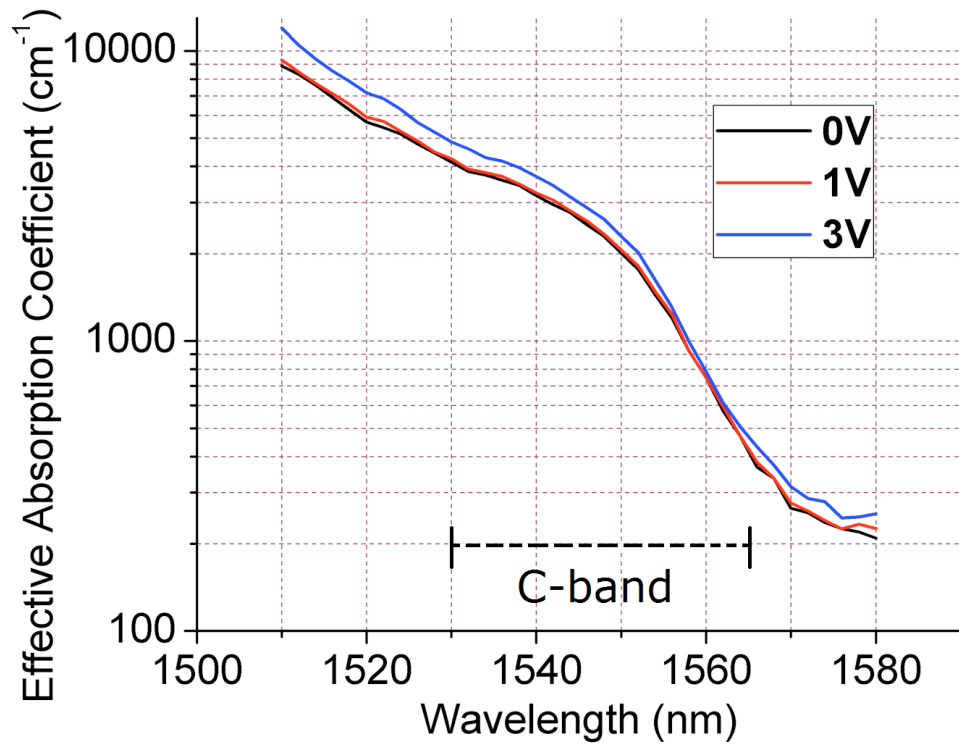


Figure 4.11 Effective absorption coefficient for various bias voltages (sample *I18* with mesa diameter of 100 μm)

Effective absorption coefficient is slightly increased with the applied field, however electro-absorption behavior is not observed. For thin QWs (~ 5 nm), lowest confined energy states lie at higher energy levels and according to the theoretical calculations based on the confined energy states, heavy-hole excitonic peak $\langle e1|E|hh1\rangle$ corresponds to the ~ 0.929 eV (1334 nm) of energy. Hence, exploiting the QCSE with thin QWs is relatively harder since the electro-

absorption phenomena takes place at the band edge. Furthermore, high electric field is needed for enabling electro-absorption, which is not a power efficient solution. However, high detection efficiency at zero bias makes sample *I18* a promising candidate for the photodetector part of an optical interconnect system operating at conventional C-band telecommunication range (1530-1565 nm).

For electro-absorption operation at longer wavelengths (especially C-band), thicker QWs should be utilized to reduce the energy of the lowest confined state. Electro-absorption behavior of sample *I19* with 10 nm QW thickness is investigated for the purpose. Figure 4.12 shows the photocurrent data of *I19* sample (10 nm Ge/20 nm Si_{0.1}Ge_{0.9}).

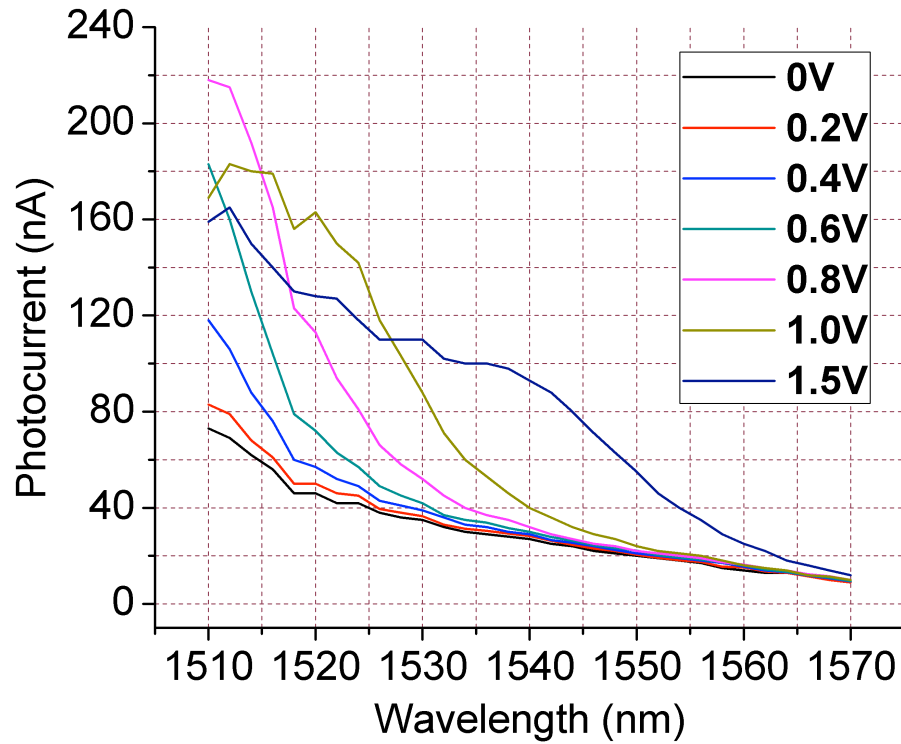


Figure 4.12 Photocurrent (nA) vs. Wavelength (nm) for various bias voltages (sample *I19* with mesa diameter of 120 μm)

As a first notice, electro-absorption behavior is observed after a threshold field ($> 1 \text{ V}$) for which the energy separation of lowest confined states ($\langle e1|E|hh1\rangle$) reduces and overlapping of the wavefunctions increase as the

shape of the wells are significantly modified with the field. Applied electric field is further increased to expose the QCSE much stronger. Figure 4.13 depicts the responsivity data of sample *II9* for higher fields.

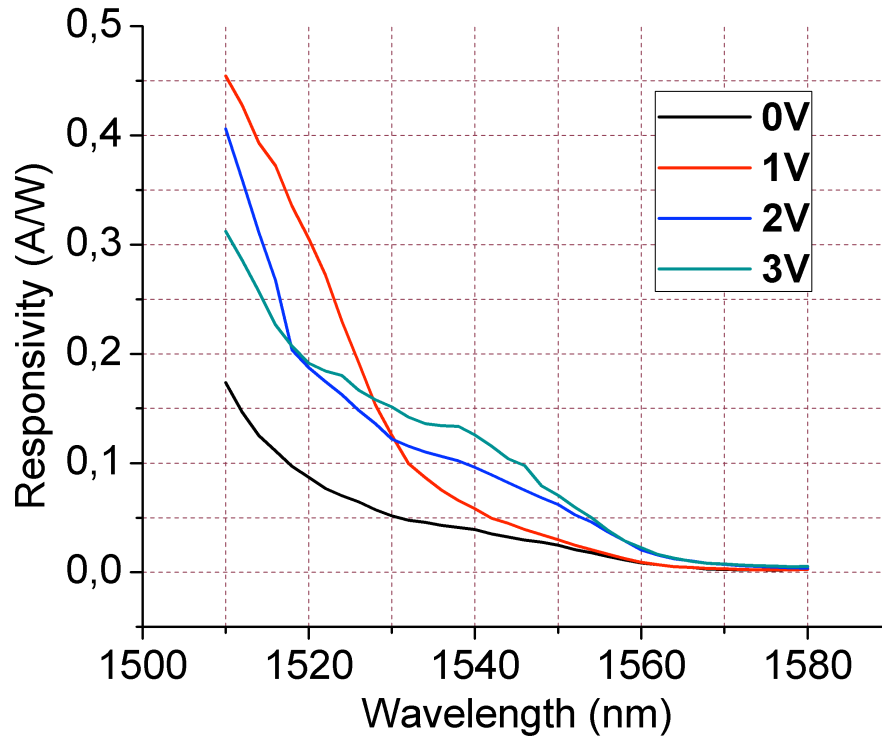


Figure 4.13 Responsivity (A/W) vs. Wavelength (nm) for various bias voltages (sample *II9* with mesa diameter of 120 μm)

Higher electric fields reduce the effective band gap and significant absorption enhancement is observed for especially $\lambda > 1530$ nm. Note that, photoresponse beyond 1550 nm (0.8 eV) is also observed due to the electro-absorption behavior and also strain effect. Photoresponse (>1550 nm) at zero bias condition also proves the contribution of indirect absorption and strain related band gap suppression. Effective absorption coefficient is plotted to clearly analyze the modulator operation in terms of given performance parameters (contrast ratio, insertion loss, figure of merit, etc.) in Chapter 2. Figure 4.14 shows the effective absorption coefficient spectra.

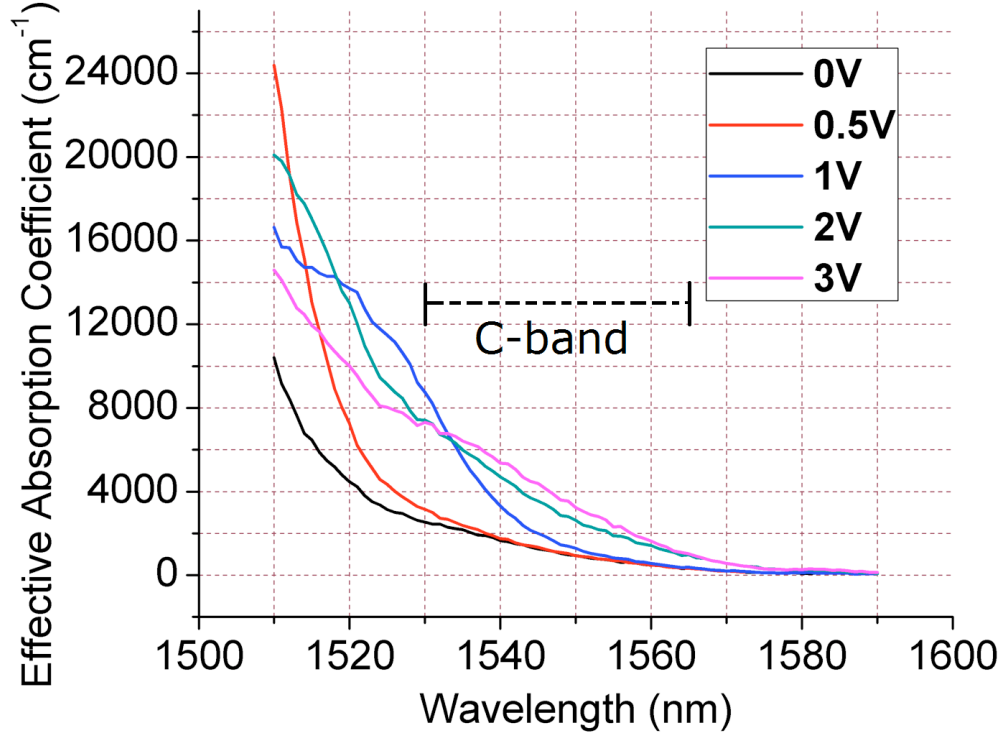


Figure 4.14 Effective absorption coefficient spectra for various bias voltages (sample *119* with mesa diameter of 120 μm)

Red shift of the absorption behavior is noticed for increasing bias voltages exploiting QCSE. Heavy-hole excitonic peak spectral location is calculated to be at ~ 0.855 eV (1450 nm). Although excitonic peaks are expected to be observable at room temperature (thanks to the quantum confinement), they are not observed due to the lower wavelength limit of the tunable laser.

As shown in Figure 4.15, peak absorption coefficient contrast ($\alpha_{\text{off}} / \alpha_{\text{on}}$) at 3 V bias is achieved for 1550 nm with 3.41 (which corresponds to a 2284 cm⁻¹ absorption coefficient change) and larger than 3 for C-band (1530-1565nm) range. Data fluctuation is observed for the wavelengths beyond ~ 1560 nm since the acquired photocurrent is in the order of tens of nA (approaching noise level). Peak contrast of ~ 3.7 for 1 V bias operation is achieved at 1526nm with an absorption coefficient change of 8146 cm⁻¹. Achieved absorption coefficient contrast is comparable with the reported Si_xGe_{1-x} based indirect gap [36] and high performance direct gap III-V electro-absorption modulators [59].

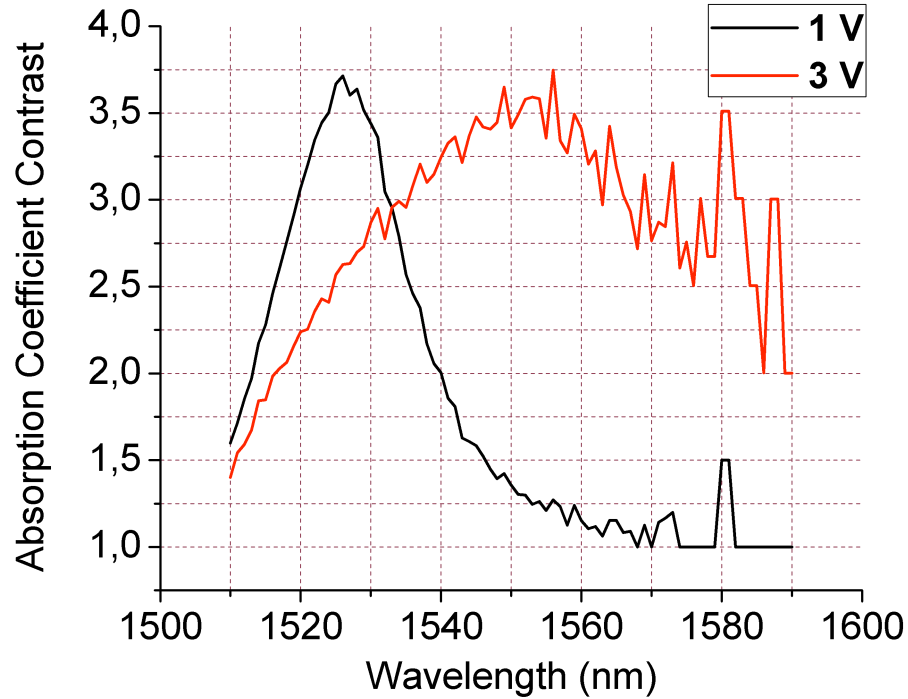


Figure 4.15 Absorption coefficient contrast with respect to wavelength (sample 119 with mesa diameter of 120 μm)

Large absorption coefficient contrast with low applied field (1 V) is achieved at lower wavelengths (1510-1530 nm) since the photon energy of the incoming radiation is comparable with the resulting effective band gap. Applied electric field should be further increased to reduce the effective band gap and enable the absorption of lower energy photons (C-band range).

A figure of merit that is defined as the ratio of the contrast ratio to the insertion loss (both in dB scale) gives information evaluating the modulator performance. As discussed in Chapter 2, an ideal modulator is expected to be transparent for “optically on” state and absorb all incident radiation for “off” state. Therefore, insertion loss should be minimized for the operational wavelength range and the contrast ratio should be further increased. Figure 4.16 depicts the contrast ratio and insertion loss and comprises worthy information in terms of modulator performance.

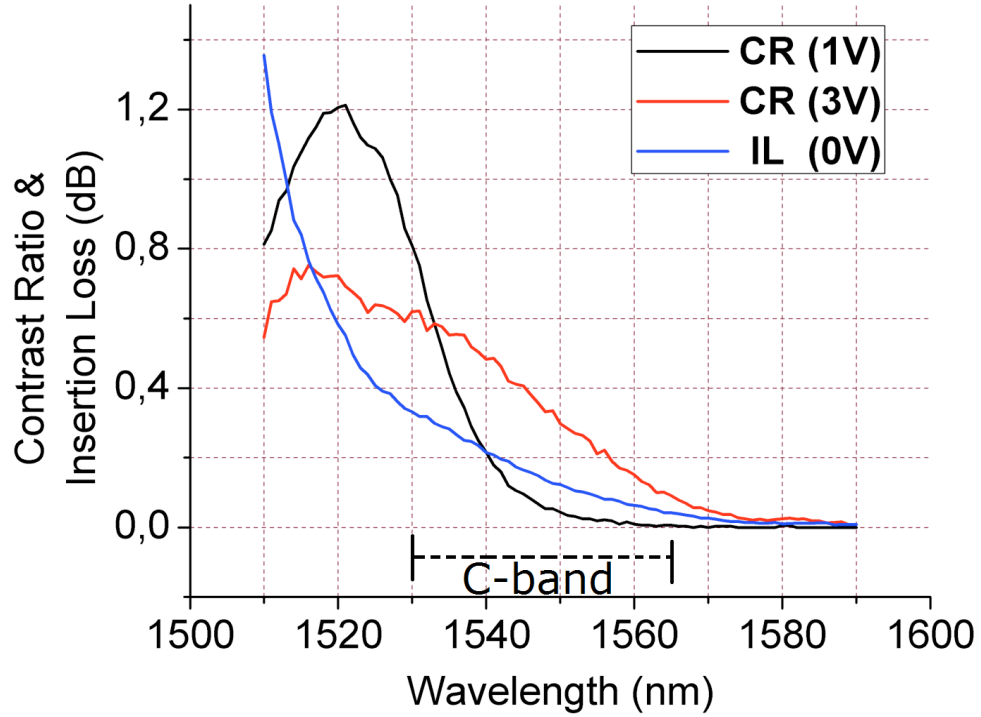


Figure 4.16 Contrast ratio & Insertion loss respect to wavelength (sample *I19* with mesa diameter of 120 μm)

As expected from previous discussion, contrast ratio increases with the increasing field for longer wavelengths. Meanwhile, insertion loss is large mainly due to the direct band gap absorption for shorter wavelengths and decreases in a nonlinear fashion as the wavelength is increased towards C-band range. In other words, the modulator behaves more “transparent” for this particular range. Hence, sample *I19* exhibit higher modulator performance (large figure of merit) for C-band wavelength range with high contrast ratio at “optically off” state and low background absorption at “optically on” state. Based on our knowledge, demonstrated electro-absorption modulator is a novel, high performance device in terms of contrast ratio and insertion loss at C-band operation range.

Chapter 5

Conclusions and Future Directions

In this study, material and device characterizations of *MHAH*-grown *p-i-n* Ge/Si_xGe_{1-x} MQW structures are investigated. High performance photodetector and electro-absorption modulator operation exploiting QCSE is demonstrated. Demonstrated photodetectors exhibit low dark current and high quantum efficiency with the quality of grown layers. Reported electro-absorption modulators are optimized for C-band (1530-1565 nm) operational range with high contrast ratio and low insertion loss. Modulation performances are highly comparable with conventional III-V devices. Represented optoelectronic devices are building blocks for optical interconnect architectures. Furthermore, monolithic integration and compatibility with Si CMOS technology renders them promising candidates for the integration of electrical and optical circuitry.

Some future directions may further improve the device performances and open path for the designation of novel devices. From the photodetector point of view, for the improvement of detection efficiency, devices with thicker intrinsic region can be demonstrated. Transparent ohmic cap layers may further improve the efficiency. Additionally, post-annealing of the samples can further improve the dark current performance and exhibit low power devices. For the electro-absorption modulator case, optical characterization for wider spectral range can be conducted to observe the device responses for shorter wavelengths. Temperature dependency on operational wavelength can be observed for tunability. A more challenging task, the integration of presented photodetectors and electro-absorption modulators with on-chip waveguide schemes may be performed to demonstrate state-of-art optical interconnect system.

Appendix

SIG E HETEROSTRUCTURE GROWTH: MULTIPLE HYDROGEN ANNEALING FOR HETEROEPITAXY (*MHAH*)

The demand for monolithic integration of Ge with Si is obvious, since Si-based optoelectronics is near-infrared-blind. On the other hand, direct heteroepitaxial growth of Ge on Si is hampered due to the lattice mismatch in between (4.2%). Lattice mismatch results with i) high density misfit and threading dislocations and ii) high surface roughness resulting with island growth. Several heteroepitaxy techniques are developed to overcome threading dislocations as discussed in Chapter 1. Nayfeh *et al.* [21] developed Multiple Hydrogen Annealing for Heteroepitaxy (*MHAH*) for high quality growth of Ge with very low threading dislocation density and surface roughness. Note that, *p-i-n* MQW architectures are developed by Dr. Ali Kemal Okyay at Stanford University using this novel epitaxy technique. This part comprises an overview related with this growth [19].

Heteroepitaxy of Ge on Si

Heteroepitaxial growth of Ge on Si is performed using a cold wall ASM Epsilon-two reduced pressure chemical vapor deposition (RPCVD) system. Typical depositions are carried out with a rotation rate of 35 revolutions/min and the base pressure of the RPCVD chamber is 0.49 mTorr. The reaction gases used are SiH₄ for Si and GeH₄ for Ge deposition. H₂ is flown into the reactor for controlling the reaction pressure. Figure A1 shows the wafer handling section of the CVD tool.

In a CVD process, there are seven main steps [60], as highlighted with numbers in Figure A2. The reactants are transported to the deposition region (1) followed by diffusion of reactants from the gas stream through the boundary layer to the wafer surface (2). The reactants are adsorbed on the wafer surface

(3). Chemical decomposition and reaction take place on the surface accompanied with surface migration to attachment sites (4). Byproducts are desorbed from the surface (5), and flow to the main gas stream by diffusion (6). Finally, a thermal process is used to force away the byproducts from the deposition region (7).

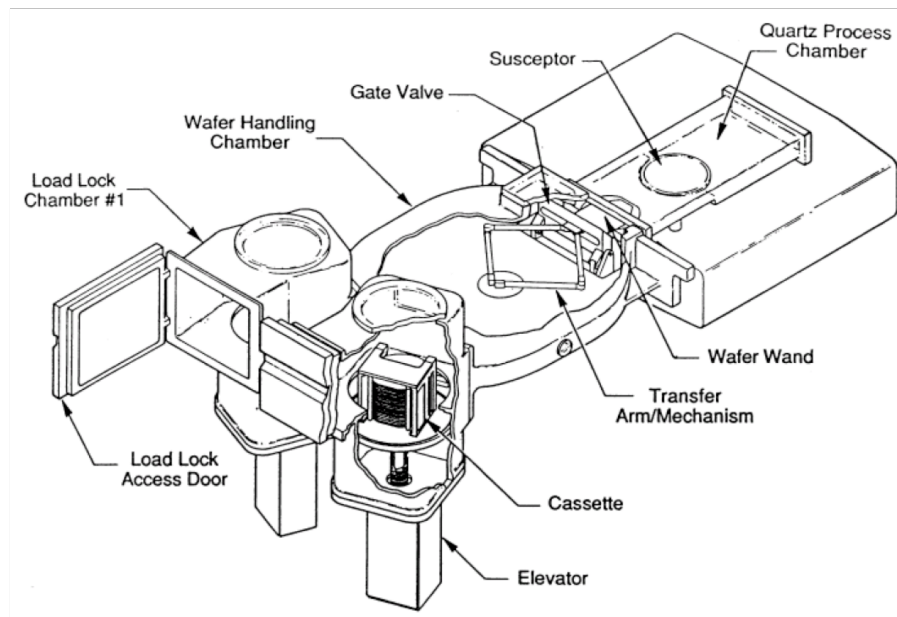


Figure A1 – ASM basic wafer-handling section drawing, courtesy of ASM Epitaxy
(After Ref. [19])

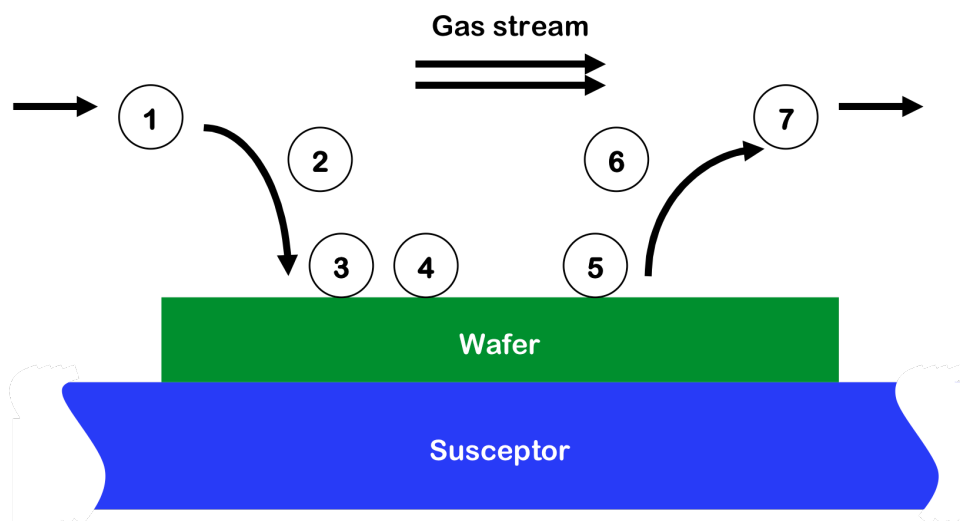


Figure A2 – Steps of CVD process (After Ref. [19])

The starting substrates are 4" *p*-type Si (001) wafers. An ultra-clean surface before the epitaxy is essential in order to ensure good crystal quality. The organic and gross contaminants such as scribe dust are removed using a 4:1 volume ratio mixture of sulfuric acid (H₂SO₄) and hydrogen peroxide (H₂O₂) at 90°C for 10 minutes. Thin oxide on the surface of Si substrate is removed by a dilute hydrofluoric acid (HF). Following the removal of organics, the wafers are cleaned in a 5:1:1 volume ratio mixture of de-ionized (DI) water, hydrochloric acid (HCl) and H₂O₂ at 70°C for 10 minutes in order to remove alkali ions and other metallic contaminants. The wafers are kept in the load lock for 30 min where they are purged with nitrogen to drive out any additional moisture on the surface. This step also helps avoid oxygen incorporation into the process chamber during wafer transfer. During this step, the process chamber is etched to remove deposition residuals from the previous run.

The wafers are immediately loaded into a reduced pressure epitaxial reactor. Before each growth, the wafers are baked in hydrogen ambient at 1000°C for 5 minutes followed by growing a thin seed layer at 700°C. This layer ensures an ultra-clean surface for starting Ge growth. Temperature is then reduced to 400°C and a 180-nm-thick *p*-type Ge buffer layer is grown. Wafer temperature was ramped up to 825°C and baked for 20 minutes in hydrogen ambient. Annealing enhances diffusion and gliding of dislocations yielding a smoother surface. Dislocations annihilate during this anneal. The temperature is set to 400°C again, the previous growth and anneal steps were repeated. Further growth is done to obtain undoped MQW regions on Ge virtual substrates, which are obtained by multiple grow-anneal cycles. Alternating Ge well region and Si_xGe_{1-x} barrier regions are grown at 400°C. No intermediate annealing is performed to avoid inter-diffusion of Si and Ge and diffusion of doping species from underlying highly doped regions. Finally, a 100-nm-thick *n*-type Ge layer is grown as a cap and for ohmic contact to the *p-i-n* device.

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