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GERMANIUM BASED DEVICES INCLUDING APPLICATIONS: A PERSPECTIVE REVIEW

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ABSTRACT

Germanium single crystal with high crystalline perfection is nowadays among the purest elemental semiconductor material available as a result of years of perfecting its growth techniques. A lot of progress in the crystal-growth techniques of nanostructure devices have been achieved of recent, such as the Czochralski and Molecular beam epitaxy or Metal-organic chemical vapor deposition (MOCVD) that allow for the formation of crystalline layers with atomic precision. With these methods the realization of quantum structure devices can be achieved by growing on top of a smooth substrate a material with a different lattice constant. Atoms in a perfect crystal are orderly arranged. Single crystal Germanium is a well-investigated material that is applied in many advanced microelectronic and optoelectronic devices such as, optoelectronics, bio-imaging, solar cells, field effect transistors, fiber optic cables, polymerization catalyst and gamma-ray detector etc, Germanium as light source emit at 1550 nm wavelength and high performance photodetectors, modulators, waveguides and other components have been demonstrated. There are still so many areas of application of this important semiconductor material particularly now at the nanoscale.

Keywords: *Germanium, crystalline, quantum structure, lattice constant, optoelectronic, transistor*.

INTRODUCTION.

Germanium (Ge) is being considered by the semiconductor community as a mainstream material for nanoelectronic applications due to its excellent and attractive material properties that can provide solutions for some bottlenecks than Silicon (Chroneos and Bracht, 2014; Claeys and Simoen, 2007). It is still a comparatively rare element. Compared to Silicon, Germanium has lower band gap energy and offers the highest bulk hole mobility amongst all semiconductors, thus offering appealing opportunities for advanced device scaling (to the order of 100 nm) such as lower drive voltages and higher drive currents for high speed electronics (Sze, 1981;

Kamalian *et al*, 2016).The electron and hole mobility is the rate at which these carriers can move through the material. There is a strong correlation between the carrier mobility of a material and the efficiency and speed of the device composed of that material. Ge also offers the advantage of processing with easier integration into conventional devices. Furthermore, though Ge and GaAs show only a slightly lattice mismatch, germanium possesses better enhanced high crystallographic perfection compared to gallium arsenide, fulfils one of the main criteria to be considered as a substrate for epitaxial III-V growth with viable applications in the areas of solar cells and related different devices(Claeys and Simoen, 2007). Indeed, Ge as a semiconductor material has gained renewed interest recently in electronics and optoelectronics (Dunwei, 2007). Today, Germanium's excellent electronic properties are exploited as there is a growing demand for faster computers, higher efficiency photovoltaic and more sensitive detectors (Evarestor, 2014).As new technologies emerged and the miniaturization of devices and structures become more and more applicable, the use of purer semiconductor materials allows one to produce smaller and smaller structures. Germanium being of great technological importance, its fields of application range from semiconductor industries, optical and telecommunication industries (in the form of pure element and its compounds with sulphide and other chalcogenides) to applications in the biomedical field (in the form of its organic derivatives). Germanium single crystal is comparatively a rare elemental semiconductor though widely used in various electronic and optoelectronic devices including magnetoresistive sensors, high electron mobility transistors, light-emitting diodes and lasers. However, a considerable research effort is needed in order to establish an updated knowledge-based germanium that will surely be required to develop and improve this material further for possible applications in advanced nanoelectronic devices fabrication.

This work is focus on presenting an updated review of the development and improvement of germanium based devices including applications.

Basic Properties of Germanium

Germanium as an important group IV semiconductor possesses a number of properties that make it very useful in microelectronics and optoelectronic applications. Table 1.1 reports the main physical properties of Ge in comparison with other semiconductors. Driven by this excellent attractive property, such as, band gap, high melting point, small effective masses, large exciton Bohr radius, high absorption coefficient and as a covalent semiconducting element, germanium has found use in many areas including optoelectronics, bio-imaging, solar cells, field effect transistors, fiber optic cables and polymerization catalyst (Wei, 2018; Dutt, 2012; Goley and Mantu, 2014).

Table 1.1: Physical properties of Germanium and other semiconductor materials (Sze, 1981; Kamata, 2008).

S/N	Property	Si	Ge	GaAs	InP	InSb	Anthracene
1	Electron mobility (cm^2/V.s)	1400	3900	8500	5400	77000	≈ 1
2	Hole mobility (cm^2/V.s)	450	1900	400	200	850	≈ 1
3	Lattice Constant(nm)	0.543	0.566	0.565	0.587	0.648	6.04-11.16
4	Electron effective masses(m_e^*/m_o	0.98^{l},0.19^{t}	1.64^{l},0.082^{t}	0.067	0.077	0.015	-
5	Hole effective mass(m_h^*/m_o	0.16^{lh},0.49^{hh}	0.04^{lh},0.28^{hh}	0.082	0.64	0.40	-
6	Bohr Radius (nm)	5	24	-	-	-	-
7	Melting point/°c	1412	937	1240	1060	525	217
8	Static dielectric constant	11.7	16	13.1	12.4	17.7	3.2
9	Band gap $E_g(eV)$	1.12	0.66	1.42	1.34	0.17	4.0

As can be observed from the Table, germanium is characterized by smaller effective mass for electrons and smaller effective mass in the heavy hole (hh) and light hole (lh) bands compared to silicon. A small effective mass of carriers leads to high carrier mobility. This property is most advantageous over silicon for scaled metal-oxide semiconductor field effect transistor (MOSFET) applications regardless of saturation velocity of silicon. Germanium has the highest hole mobility of all known semiconductor materials. It offers nearly two times higher electron mobility than silicon, but it is still a relatively small value compared to other materials e.g. III-V material (InAs, InSb etc) However, the electron and hole mobility of germanium are more balanced with a significant advantage for the current state of the art logic design in complementary metal-oxide semiconductor (CMOS) based on symmetric configuration of both n-type and p-type transistors (Pillarisetty, 2011). This feature is important in microelectronics because conductivity is proportional to the product of mobility and carrier concentration. These values hence emphasize that germanium is better than silicon in the fabrication of new generation high speed microelectronic devices in high mobility channels.

Another important parameter is the material's band gap. Germanium is an element of group IV with an indirect band gap of 0.66 eV at lower temperature lower than that of silicon (1.12 eV). This parameter influences the scalability of electronic devices (e.g. MOSFET) by affecting the threshold voltage and consequently driving voltage of device. Shirahata *et al*, (2012) have reported that lower band gaps and higher carrier mobilities offer appealing opportunities for advanced device scaling such as lower drive voltages and higher drive current for high speed electronics as well as possible tuning of light emission over as much as 3.3 eV with wavelengths in the near ultra-violet through visible to near infrared. Performance of nanoelectronic devices based on germanium is characterized by low thermal noise at low supply voltage of about 0.5 V has already been successfully demonstrated (Pillarisetty,2011). Moreover, because of its quasi-direct band gap, germanium absorbs light much better than silicon. This peculiarity is related to the lower value band gap, very high mobility of charge carriers and the nearly-direct nature of its band gap with respect to silicon. The capability to absorb light also in near infrared range (where bulk silicon is optically transparent) combined with its high carrier mobility (related to the lower effective mass for electrons and holes in germanium (Claeys and Simeon, 2011) enhanced germanium as a viable candidate for the fabrication of high speed devices. Furthermore, germanium shows an exciton Bohr radius (24 nm) well larger than that of silicon (□5nm) (Maeda *et al*, 1991). This means it is possible to easily tune the absorption edge of germanium nanostructure from the infrared across the visible range without the need to shrink too much the nanostructure size. Germanium has a larger lattice constant (0.564 nm) than silicon(0.543 nm) and a lower melting point in comparism to silicon. Germanium is easily integrated with silicon as both are members of group IV of the periodic table and form a crystalline alloy of any silicon/germanium composition. Germanium nanoparticles have a larger exciton Bohr radius thus, enhancing a strong quantum confinement independent of the large nanocrystals radius. Though bulk germanium is an indirect band gap material, nanocrystalline germanium is found to behave as a direct band gap material. Germanium nanocrystals exhibiting strong visible photoluminescence have been prepared by several methods (Niquet *et al*, 2000). Takeoka *et al*, (1998), have observed size dependent photoluminescence in the near infrared region which is closer to the band gap of bulk germanium. It is also suggested that radiation recombination in germanium nanocrystals could be faster because of the small energy difference between the indirect and direct band gap. Due to the narrow band gap (0.66 eV) and large Bohr exciton radius of germanium, it is possible to tune the photoluminescence of germanium quantum dot throughout the visible spectrum just by making small changes in the dimensions of the particle. These properties make germanium appealing to many optoelectronic applications (Steiner, 2004).

Germanium Based Devices

It is important to acknowledge that the alternative applications of germanium stems from its attractive material properties. The energy levels of the top of the valence band and bottom of the conduction (the respective band edges) define the energy gap as $E_g = 0.66$ eV. The high charge carrier mobility or particularly the band gap nature together with the high compatibility with the already existing Si-based technology, led to recent renewed interest towards germanium as a primary ingredient in a new generation high-speed devices (Pinto *et al*, 2006).

Optical Modulator

It is indispensable in any optical interconnection system. Optical modulation is the process of varying a property of light e.g. phase, frequency, polarization or intensity according to an applied electrical signal. The role of the modulator is to impress information on the light carrier. It allows much higher data and multilevel modulation format, the system is less expensive and has better temperature stability because a sophisticated light source is not needed, a single light source could be used for different channels with separate optical modulators. Various factors decide the performance of the modulator: modulation depth, modulator speed and bandwidth. In an ideal case, preferably high modulation speed, large bandwidth and low power consumption. Optical modulators generally come in different flavors such as electro-refraction modulators, electro-absorption modulators (which are directly integrated into a waveguide), ring resonator and Mach-Zehnder modulator. These effects are fundamentally connected via the optical susceptibility of the material and both can be changed by the application of direct current (D.C) electric field. Modulation may be imposed on the phase, frequency amplitude or polarization of the light beam.

Electro-Refraction Modulator

This modulator relies on phase shift or change in the polarization of the optical beam passing through an applied electric field. The consequent constructive or destructive interference of the phase shift or polarization changed optical beam produce the modulated output. This type of modulation is described as electro-optical modulator. The difference in phase or polarization is a direct result of electric-field induced refractive index change. To understand how the refractive index of the material is changed by the applied electric field, we have to recall the electric field relationship to the displacement vector that is given as (Miller, 2007):

$$P = \varepsilon_o \chi_e E; D = \varepsilon_o E + P = \varepsilon_o \varepsilon_r E = \varepsilon_o (1 + \chi_e)\mathrm{E} \tag{1}$$

$$D = \varepsilon E \tag{2}$$

$$n = (1 + \chi_e)^{\frac{1}{2}} \tag{3}$$

where D is the magnitude of the electric displacement vector, P is the polarization density, E is the electric field, ε, χ_e, n are dielectric constant, dielectric susceptibility and refractive index respectively. The applied electric field changes the permittivity tensor and the permittivity is square of the refractive index. Further description of electro-optic modulators is based on the physical structure of the device.

Electro-absorption modulators

Electro-absorption modulators are based on the change in the imaginary part of the refractive index of a material due to an applied electric field. The absorption mechanism is due to the free carriers or as a result of assisted direct transition of carriers near the band edges. In an electro-absorption modulator, a variation of light intensity at the modulator output according to the applied electric field is obtained through the variation of the absorption coefficient of the wave guide material. ON/OFF states correspond to the situation of low absorption coefficient and high absorption coefficient respectively. In an electro-optic modulator, the phase of the carrier is varied according to the applied electric field through the variation of the refractive index of the material. An integrated interferometer is typically used to convert the refractive index induced phase modulation into the intensity modulation. Basis physical phenomena by which electro-absorption modulation are possible include Pockels, Kerr, Franz-Keldysh and Quantum confined stark effects. The Pockels effect or linear electro-optic phenomenon causes birefringence in an optical medium by a change in the real part of the refractive index which is proportional to the external electric field. This effect typically occurs in crystals that lack inversion symmetry such as lithium niobate ($LiNbO_3$) or III-V materials (GaAs, InP) and in other non-centro-symmetric Medias like polymers or glasses. The Kerr effect also called the quadratic or second order electro-optic effect is a change in the real part of refractive index of a material in respond to an applied electric field. The change of the refractive index is proportional to the square of the external electric field. All materials show Kerr effect, however, it is generally masked by the much stronger linear effect. The Kerr effect plays a dominant role in centro-symmetric materials like silicon and germanium. In devices which use these effects the refractive index is modulated by modulating an applied voltage which control the electric field across the material. The Franz-Keldysh effect is an electric field induced change in the optical absorption spectrum of a semiconductor. When an external electric field is applied, energy bands of the semiconductor bend and the expansion of electron and hole wave function in the band gap are modified. Consequently, it influences absorption processes assisted by a photon with energy smaller than the bulk band gap leading to changes in the shape of the fundamental absorption edge of a semiconductor towards longer wavelength values. Contrast to Pockels and Kerr effects, the Franz-Keldysh effect is based on the change of both real and imaginary part of the refractive index. The complex refractive index of a material can be written as n+ik, where n is the refractive index of the complex material, k is the imaginary part of the complex material and is called the extinction coefficient. When light is absorbed in passing through a medium from one point to the other, the extinction coefficient is related to absorption coefficient (α) by $K = \frac{\alpha\lambda}{4\pi}$ where λ is the optical wavelength, the real and imaginary parts of the complex refractive index are related by the Kramers-Kronig dispersion relation that holds for Δn and ΔK. This Kramers- Kronig coupling between Δn and ΔK is written as (Yu and Cardona, 1996):

$$\Delta n(\omega) = \frac{c}{\pi} p\int_0^\infty \frac{\Delta k(\omega')d\omega'}{\omega'^2 - \omega^2} \tag{4}$$

$$\Delta k(\omega) = -\frac{c}{\pi} p\int_0^\infty \frac{\Delta n(\omega)d\omega'}{\omega'^2 - \omega^2} \tag{5}$$

It is interesting to note that the Kramers- Kronig transformations arise for purely mathematical reasons simply from requesting that the perturbation-response relationship is casual (i.e. no response before the perturbation take place) and that the response function is well-behaved. The real part of the response function describes a refractive property (refractive index, optical rotation etc) whereas the imaginary part describes an absorptive property (electronic absorption spectrum, circular dichroism, etc). The absorption change with the applied electric field is given as

$$\Delta\alpha(E,\xi) = \alpha(\omega,\xi) - \alpha(\omega,0) \tag{6}$$

where E is the energy of the light and ξ is the applied electric field. Thus, in the Franz-Keldysh effect, the electric field involves the change in both the absorption coefficient and in the refractive index. This effect occurs in uniform bulk semiconductor materials, but usually requires strong electric fields (hundreds of volts/cm). Chaisakui *et al*, (2014), reported that silicon possesses a weak electro-optic effect due to its indirect band gap i.e. a global minimum of the conduction band at the valley far from the zone center. As a result, the indirect absorption dominates all the optical processes leading to poor efficiency of optical devices made of silicon. The III-V direct band gap semiconductors are widely used in nowadays long-haul and intermediate distance telecommunication networks (Chaisakui *et al*, 2014). However, unlike silicon bulk germanium shows a significant Franz-Keldysh effect which gives this material a clear perspective to be used as light modulator in integrated circuits (Frova and Handler, 1965). It has been reported that strong electro-optic effect for germanium can be further improved by tensile strain engineering so that the strength of refractive index change starts to be comparable to InP and $LiNbO_3$ (Jongthammanurak *et al*, 2006). A successful monolithic integration of germanium-based modulator into a silicon waveguide on Si-on-insulator was demonstrated (Liu *et al*, 2007; Lim *et al*, 2011). In both works, fully functional novel germanium electro-absorption modulators of high efficiency, radio frequency signal modulation and low power consumption were presented. In addition, it was shown that the efficiency of novel germanium modules is fully comparable to existing silicon micro ring resonator and Mach-Zehnder interferometer.

Quantum confined stark effect

This phenomenon similar to Franz-Keldysh effect which was first observed in GaAs/AlGaAs multiple quantum well structures is a strong alternative to realize high performance optical modulators. As a breakthrough, Kuo *et al*, (2005), reported strong quantum confined stark effect in $Ge/Ge_{0.81}Si_{0.15}$ multiple quantum wells, opening a new way to integrate high performance modulators on silicon. The interest of using quantum well structures results from its discrete energy levels, thanks to the quantum confinement effect.

For optical modulation, this leads to a sharper rise of the absorption edge than in the bulk material. Electrons and holes within the quantum well only occupy states within a discrete set of energies. In consequence, only a discrete set of frequencies of light is absorbed or emitted by the multiple quantum well system. This situation is changed when an external electric field is applied. Electron and hole wave functions are pulled towards opposite sides of each quantum well, for example, the electron states shift to higher energies. Consequently, the permitted light absorption and emission frequency changes, as a result of decrease in wave function overlapping. As regard the potential application of germanium, quantum confined stark effect was demonstrated in germanium quantum wells and Ge/SiGe super lattices (Kuo *et al*, 2005). The electric field at which significant electro-absorption are observed fall in the range $10^4 - 10^5$ V/cm (Meenakshi *et al*, 2010). The discovery of strong quantum confined stark effect is reported in compressively strained germanium quantum well with SiGe barriers (Roth *et al*, 2007). Stark based devices are faster and operate in excess of 40Gb/s. Polarization dependence of quantum confined stark effect from Ge/$Ge_{0.81}Si_{0.15}$ multiple quantum well has also been explored theoretically and experimentally (Chaisakui *et al*, 2014).

Mach-Zehnder Modulator

This is an example of an electro-optic modulator. From Figure 1, two optical beams travel through the two phase shifters inserted in the arms of the interferometer and combine at the output. An applied electric field from voltage bias alters the refractive index of one of the waveguides in one of the arms thereby causing a 90^0 phase shift relative to the other waveguide. When the optical beam is combined the phase shift results in a destructive interference of the optical signal. On the contrary if the signals on the two waveguides are of the same phase, they combine constructively and enhance the optical signal. To implement this type of modulator, information is encoded into the electrical signal as voltage levels. The optical channels are biased to produce phase shift corresponding to the electrical voltage level, thereby encoding the electrical signal into optical signal (light modulation). A sketch of this type of modulator structure is a long millimeter device required to achieve a significant modulation, leading to high energy consumption in the order of picojoules per bit pJ/bit. Extremely, high data rate optical communication requires external Mach-Zehnder intensity modulators for high speed, adjustable-chirp modulation for optical signal. Other applications of Mach-Zehnder modulators include the distribution of cable television signals, antenna remoting and instrumentation. One figure of merit of the modulator is the product of voltage and length ($V \times L$) needed to produce 180^0 phase shift and thereby switch the output from 'on' to 'off'. This modulator gives a total insertion loss of 19dB consisting of 9dB coupling loss and 10dB on-chip loss. Phase efficiency can be further improved by reducing the wave guide dimensions and reducing the gate dielectric width.

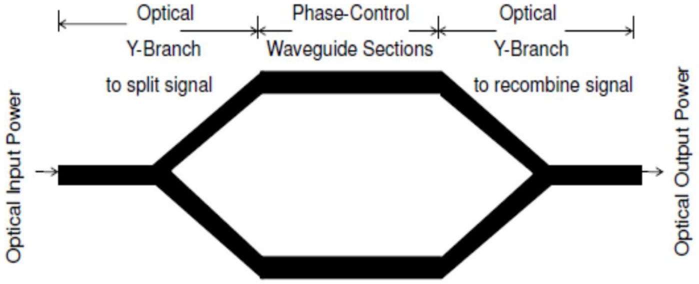

Figure 1: Schematic View of Mach-Zehnder Modulator [Saleh and Teich, 1991].

Ring resonator waveguide modulator

It is based on a ring waveguide near a straight waveguide (Figure 2 for the view of a ring resonator). To realize an optical modulator, the phase shifter is inserted in the ring. Light coming from the straight waveguide is coupled into the ring. The coupling of the light from the straight waveguide to the ring depends on the gap between the waveguides. After propagating in the ring, light is coupled back to the straight waveguide. The transmission from the ring will be minimum when the ring circumference matches the resonance condition $nd = \frac{\lambda}{2} p$, where n and d are respectively the index of refraction and the circumference of the ring, p is an integer. When no bias is applied to the phase shifter integrated into the ring, the transmission present sharp minima at some wavelength. When a bias is applied to the phase shifter in the ring the phase shift that is encountered by the optical mode propagating in the ring varies and the resonance (resonant wavelength are shifted) is shifted and the transmission from the ring at a given wavelength varies. The power consumption is reduced by using a ring resonant structure but it is sensitive to fabrication defects due to its highly resonant character.

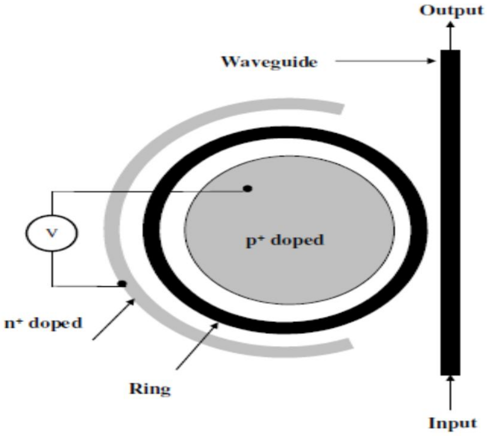

Figure 2: Schematic view of a ring resonator [Lim *et al,* 2008]

Germanium Photodetector

A photodetector is a device that absorbs optical energy and converts to electrical signal which usually manifest as a photocurrent. It is widely applied in optical communication system where detectors receive the transmitted optical pulse and convert them with as little loss as possible into electronic devices. An efficient photodetector is characterized by high sensitivity at operating wavelengths, high response speed, low cost, high reliability, wide bandwidth and high signal-to-noise ratio. Many silicon photonic integrated devices have been demonstrated successfully particularly ultra-compact passive devices. However, the intrinsic properties of silicon make it challenging to realize active and efficient photonic integrated devices like lasers, modulators and Photodetectors. For example, the relative large band gap of silicon (1.12eV) which simultaneously determines an absorption cut-off wavelength around$1.1\mu m$, higher wavelengths are not available for this material. For wavelengths longer than this value, the light will not be detected efficiently due to very small absorption coefficient. In order to increase the range of light detection, particularly in the range typical for telecommunication ($1.3-1.5\mu m$), other materials must be sought. Among many prospective materials, III-V compound semiconductors can be utilized. This choice seems obvious because these materials are characterized by high absorption coefficient and high carrier drift velocity required for fast response time. However, the integration of III-V semiconductors into silicon CMOS technology is still difficult. Germanium is therefore a natural alternative for III-V compound semiconductor materials due to its smaller band gap energy ($E_g(Ge) = 0.66eV$) that favors optical absorption at optical communication wavelength, low cost and its compatibility with the current CMOS technology make it an attractive material for high performance photodetector (Hartmann *et al*, 2004; Soref, 2006). Many structure type of germanium-based Photodetectors were demonstrated over the years (Kang *et al*, 2008; Bhattacharya, 2002). As an example, one of the simplest and commonly used types of photodetector is the p-i-n or n-i-p diode operating in reverse bias. The p-i-n diode is a special case of the p-n junction diode with an intrinsic layer (i) between the p- and -n regions. When an external reverse bias is applied the intrinsic layer is depleted and thus a high resistivity. An electron-hole pair is created after light absorption and the carriers are separated by a built-in-electric field, the field inside the junction contributes to the current flow in the circuit. As mentioned above, the intrinsic layer is characterized by high resistivity, which means the voltage drop takes place mainly in this region. Thus, this promotes the excitation and collection of electron-hole pairs. Usually, the intrinsic layer is thicker than the doped region for effective collection of electron-hole pairs. The main advantage of the p-i-n diode is the fact that by adjusting the thickness of the intrinsic layers, the quantum efficiency and response time can be optimized (Wang and Lee, 2011). For the intrinsic region, the generation rate per unit area decrease exponentially following the Lambert-Beer law as:

$$G(x) = G_0 \exp(-\alpha x) . \tag{7}$$

The initial generation rate $G_0 = \phi_0 \alpha$ is given by the incident photon flux per unit area, ϕ_0 and the reflectance of the surface R as:

$$\phi_0 = \frac{P_{opt}(1-R)}{Ah\nu} \tag{8}$$

The drift current in the intrinsic region collects all the carriers (if recombination in the depletion layer is neglected). The electron drift current is given by

$$J_{drift} = -e\int_0^{\omega} G(x)dx = e\phi_0[1-\exp(-\alpha\omega)] \tag{9}$$

where ω is the thickness of depletion layer. In the bulk regions ($x \geq \omega$) the minority-carrier density is determined by the drift and diffusion. In germanium p-i-n photodetector, the intrinsic layer is made of germanium for effective absorption. However, highly doped p, n regions can be realized by implantation, in-situ doping for p^+ and n^+ regions for the pin structure. Another way is to use p^+ and n^+ single crystalline silicon substrate or deposited polycrystalline silicon heterojunctions (Wang and Lee, 2011). The first Ge-on-Si p-i-n photodetector was demonstrated by Colace *et al* (2000). This photodetector integrated in silicon waveguide have demonstrated impressive results with characteristics close to those of III-V semiconductors. Similarly, Feng *et al*. (2009) have reported high speed germanium photodetector with greater 32 GHz optical bandwidth. The device operates with a responsivity of 1.1A/W at a wavelength of 1550 nm. With the technique of high quality germanium growth on silicon, many germanium-on-silicon photodetectors have been demonstrated including metal-semiconductor -metal and p-i-n devices.

Germanium Metal-Semiconductor-Metal (MSM) Photodetector

In order to achieve high sensitivity and high speed photodetector, a waveguide integrated metal semiconductor-metal configuration is utilized. A MSM photodiode consists of a piece of semiconductor (e.g. germanium) between two Schottky contacts such that the region in between is completely depleted. Metal electrodes are placed on top of the germanium layer to confine light horizontally and collect the photogenerated carriers. This can be single contact or interdigitated electrode configuration on top of an active light absorption layer. The waveguide are made of small size to allow small electrode spacing to ensure high speed operation. In this configuration, the carrier transport take place only in the germanium layer and thus imposes no electrical requirement on the waveguide layer. Consequently photonic circuits fabricated using this material can be deposited on top of CMOS chip. This is in contrast to detectors that require the use of single crystalline silicon for germanium epitaxy growth or carrier transport. Metal-semiconductor-metal photodetectors are photoconductive devices whose conductivity is altered when an optical illumination is imposed. They are functional under non-zero external bias. A small narrow band gap of germanium will result to high absorption in telecommunication wavelength. However, the small band gap leads to small Schottky barriers and in consequence large dark currents of metal-semiconductor- metal detector. Furthermore, the high current of germanium-based metal-semiconductor- metal diode is affected by the narrow band gap and strong Fermi level pinning of the metal/germanium interface at the valence band and hole injection over the Schottky barrier height. Recently, it was shown that application of dopant segregation technique or asymmetric electrode can substantially reduce dark current (Zang *et al*. 2008). The dark current of the photodetector device is determined by thermionic emission over the barrier identical to the gate metallization of field effect transistor. Therefore, its integration with field effect transistor based amplifiers is readily feasible. Okyay *et al*. (2006) have successfully demonstrated metal-semiconductor-metal photodetector in germanium grown directly on silicon using novel techniques that allows growth of high quality heteroepitaxial germanium layers on silicon. Results show that quantum efficiency were appreciable with 0.85A/W responsivity achieved at $1.55\mu m$

Germanium Avalanche Photodiodes (APD)

Photodiodes belong to the category of light sensors or detectors whose task is to convert an optical signal into an electrical signal. Avalanche photodiodes are another type of photodetectors widely used in optical telecommunication systems. By utilizing an impact ionization mechanism to provide an internal gain, avalanche photodiodes have the advantage of higher sensitivity (~5-10dB) and higher speed over conventional p-i-n photodiodes since the photocurrent is multiplied when the overall noise in the receiver module is dominated by electronic noise. This all-important gain in APD is due to the impact ionization caused by high energy carriers. In most studies, mainly III-V based APDs are used because of its high gain and large intrinsic bandwidth (Kanishka and Das, 2014) As mentioned earlier, germanium is an efficient light absorbing material in the wavelength range $1.3-1.55\mu m$. Meanwhile, Silicon has a low ionization coefficient factor (K) $\mathrm{K} \leq 0.1$(K defined as the ratio of the ionization rate of carrier (electron) type to the hole) that makes it an ideal multiplication material (Dai *et al*, 2014). Kanishka and Das, (2014) have reported that if Ge is incorporated into Si an enhanced optical absorption can be obtain at longer wavelength. Therefore, germanium/silicon platform is very attractive for realizing avalanche photodiodes. The basic operational principle of an avalanche photodiode is based on photo carrier generation in the absorption layer with high electric field and high reverse bias, the impact ionization mechanism for carrier multiplication amplifies the photo current generated and improves the sensitivity. This diode possess a separate absorption charge multiplication layer with thickness of this region decoupled from the charge density constrain in the avalanche photodiode. The multiplication gives rise to high internal current gain. Therefore, avalanche photodiode gives opportunity for detection of lower power signals. Thus, avalanche photodiodes have much higher sensitivity than standard p-i-n or metal-semiconductor- metal diodes. The key figure of merit that testifies to the efficiency of the avalanche photodiode is the absorption coefficient K. This parameter affects the excess noise, the gain bandwidth product as well as the sensitivity of the diode. For instance, small K values indicate noise decrease and hence increase of device performance. Also, the gain mechanism of the diode is very temperature sensitive because of the temperature dependence of the electron and hole ionization rate. This temperature dependence is particularly critical at high bias voltage, where a small change in temperature can cause large variations in the gain. At reduced temperature in the semiconductor device, lattice vibrational energy is reduced as well and does the scattering of electrons and holes. Ideally, avalanche photodiode only has one type of charge carrier as multiplier resulting in reduced noise. Although Avalanche photodiode based on III-V semiconductor for near infrared wavelength have been commercialized, a lot of effort has been put into researching high-speed and high efficient diodes based on germanium-on-silicon heteroepitaxial system. Germanium has excellent potential as a material for optical detection due to its possible integration with silicon technology and good optical absorption property at the near infrared wavelength. Germanium/Silicon avalanche photodiodes combine the excellent optical absorption of Ge at telecommunication wavelength with the outstanding carrier multiplication properties of silicon. In the presence of high electric field gain region of silicon, photogenerated electrons (or holes) from Ge absorption layer undergo a series of impact ionization process for carrier multiplication. Through the carrier impact ionization process, an avalanche photodiode provides more electron-hole pairs from the same amount of photogenerated carrier compared to p-i-n photodiode. It has been shown that silicon offers much better multiplication properties than typical III-V semiconductor compounds (Michael *et al*, 2010; Kang *et al*, 2008). Kang *et al*, (2008) have demonstrated the first Ge-on-Si separated absorption charge multiplication APD structure with a gain bandwidth product as high as 340GHz. Avalanche operation of Ge-based photodiodes have been demonstrated in separated absorption charge multiplication and metal-semiconductor-metal structure(Virot *et al*. 2014). The results show that the photodiode exhibit low multiplication noise and have suggested the need of high bias. On the other hand, the results of metal-semiconductor- metal structures reveal that the internal gain can be achieved at low bias, the associated dark current are high about 50 KA for unit gain. Kanishka and Das, (2014) have investigated SiGe n^+-i-p^+ APD with very thin multiplication layer for different values of Ge-content. Results are verified with experimental data taken from literature, and reasonably good agreement has been found. Also, it has been shown that as the Ge-content increases, the breakdown voltage of the APD decreases and the gain increases more rapidly for higher Ge-content.

Germanium as Light Source

The process of light emission in semiconductors is known as radiative recombination. Light emission from semiconductor materials or samples is one of its characteristic features. In an excited semiconductor there will be holes near the top of the valence band and electrons near the bottom of the conduction band. Due to the presence of holes in the valence band, the electrons in the conduction band are in an unstable high energy state. The holes in the top of the valence band constitute empty lower energy states that the electrons can fill, consequently electrons in the conduction band can release their extra energy and fill the vacancies in the valence band, recombining with the holes. The transition from a higher to a lower energy level results in an energy loss equal to the difference in energy of these levels i.e. E_g (Fundamental transition). When this energy is released as heat or as lattice vibrations, the process is called non-radiative recombination. Alternatively, if the energy is released in the form of a photon, the process is known as radiative recombination. In radiative recombination, the emitted photon has energy equal to or greater than E_g. The value of the energy band gap E_g, is a characteristic of every semiconductor (although its precise value depends on temperature) therefore each semiconductor has its characteristic light emitting frequency. Exchange data using photons is fundamentally better than the electrical representation of bits through metal wiring utilizing charge carriers. Unlike electrons and holes, photons have neither mass nor charge, resulting in a significant reduction of signal loss, delay and heating. The main source of power consumption within an optical link is the light source, modulation and demodulation stages. The CMOS industry is Silicon-based, providing mature understanding of its characteristics and processing techniques yet Silicon is a poor light emitter. Furthermore, several practical issues direct attention away from silicon, such as the efficiency and output power, blue-shift of emission wavelength (in quantum structures), leakage of optical modes into the silicon wafer, and the necessity of other materials to be used for waveguiding (Canham, 1990).

Germanium is a semiconductor material and has attracted much attention of recent as a possible monolithic light source owing to its emission wavelength of 1550 nm suitable for silicon-based waveguide in addition to the CMOS compatibility and pseudo-direct band gap character (Saito *et al*. 2014). The use of Ge in silicon-based electronic devices is widely investigated such as $Si_{1-x}Ge_x$,virtual substrates for global strain engineering and high-performance p-MOSFETs. Research has shown that the formation of nanostructure is one of the energy band engineering of silicon and germanium. Already, as mentioned above, germanium has been used to demonstrate high performance photodetector, modulators, waveguides and other optical components. More recently, interest in germanium as a group IV laser source has rapidly grown after the demonstration of optical gain and lasing using optical and electrical pumping. As a material, germanium has a more suitable band structure for direct gap inversion compared to silicon, emitting around telecommunication wavelength (1550 nm) in bulk state. It is a multi-valley indirect band gap semiconductor material having both direct and indirect band-to-band radiative recombination. Even though germanium has a direct band gap of 0.8 eV, it is intrinsically an indirect band gap material due to the presence of L-conduction band located 0.136 eV below the Γ-conduction band valley, Figure 3(a). This energy difference make germanium an inefficient light emitter as majority of externally injected electrons will occupy the lower energy L-conduction band valley. Electrons located at the L-conduction valley can recombine only with a hole with the assistance of a phonon, when the recombination rate to emit a photon is low but by filling the indirect L-valley in the conduction band, we can observe direct recombination at the Γ-point. On the other hand, electrons located at the Γ-conduction valley can recombine at higher recombination rate with a hole. Therefore, by making germanium a direct or pseudo-direct band gap material, we increase the carrier recombination rate from the Γ-combination valley and make germanium an energy efficient light emitter. Haynes and Nilsson (1964) reported that direct optical transition in germanium is a very fast process with radiative recombination rate five orders of magnitude higher than that of indirect transition. These imply direct gap emission of germanium is as efficient as that of direct gap semiconductor. The light emission from germanium can be significantly enhanced by exploiting its direct band transition (Soref, 2010; Zhou *et al*. 2015), Generally, converting germanium from a fundamentally indirect band gap material to a direct band gap material is possible by introducing tensile strain, n-type doping or alloy germanium with tin (Yasuhuko *et al*. 2003; Geiger *et al*. 2015), Figure 3(b). Both approaches reduce the band gap in germanium i.e. the band gap at the direct Γ-valley reduces at a higher rate than at the indirect L-valley, thus the band structure of germanium is modified, eventually turning germanium into a direct gap material that is capable to absorb or emit light. It is expected that the luminescence will be larger as the tensile strain is increased. It has been shown theoretically that germanium can be engineered by tensile strain and n-type doping for better direct gap light emission at room temperature (Xiaochen, 2012; Liu *et al*. 2007). The engineering of germanium band gap through tensile strain gives the possibility to develop novel optoelectronic devices such as light- emitting diodes [LED], lasers, optical modulators that are fully compatible with silicon technology (Liu *et al*. 2010). Germanium has found use in a large variety of devices spanning from energy- tunable light harvester (e.g. Photodetectors) to efficient optoelectronic devices. Various configurations of thin-film germanium based photodetector (p-i-n, waveguide coupled or avalanche gain detector design) have been developed and demonstrated high values of performance, 0.5-1 A/W at 1550 nm (Liu *et al*. 2008).

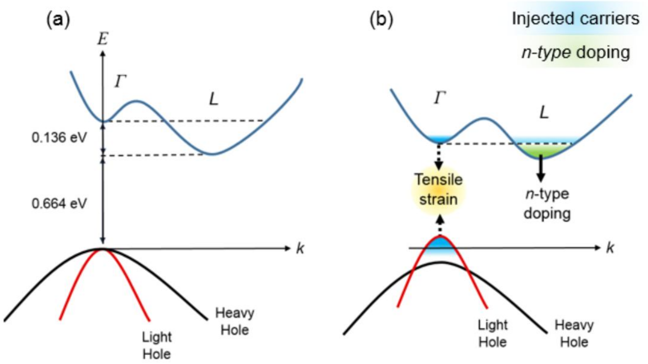

Figure 3: Germanium band gap sketch, a) bulk Ge and b) band engineering of Ge using tensile strain and n-type doping. Tensile strain reduces the energy difference between T and L-valleys, while n-type doping compensates for the remaining energy difference. Strain also induces splitting of light and heavy hole bands (Xiaochen *et al*, 2010).

High Mobility Germanium Channel Material for CMOS

CMOS technology is the dominating technology today for highly integrated circuits in electronic devices. In such devices, MOSFETs with n-channel (N-MOS) and p-channel (P-MOS) are used on the same chip. In a CMOS integrated circuit the P MOS (N MOS) device has a built-in tensile strain channel for modifying the effective mass, thus allowing higher drive current due to its high mobility. A detailed treatment and operational principle of CMOS can be found in Literature (Grundmann, 2016). One reason why silicon has been the dominant semiconductor material in microelectronic industry can be attributed to its high quality native oxide SiO_2 ,thermal and chemical stability, insulating properties and large band gap that forms an excellent interface. These performances are worse for other semiconductors such as Ge, GaAs and GaN. However, the introduction of high-K oxides to replace silica as the insulate layer makes it possible to reconsider the use of high mobility Ge and III-V channel materials as long as suitable passivation techniques are identified to obtain good interface quality between the oxide and semiconductor. High-K materials have high dielectric constant(as compared to SiO_2) used in semiconductor manufacturing process to replace SiO_2 gate dielectrics.

Ge has been considered as a promising alternative channel material for transistors, primarily due to its superior optoelectronic properties such as high carrier concentration, high carrier mobility, pseudo direct band gap and compatibility with conventional Si CMOS technology. For example, combining higher carrier mobility and higher absorption coefficient (wavelength range 800 nm to 1550 nm) compared with Silicon makes Ge a feasible candidate for modulators on CMOS circuits for optical interconnection and the integration of optical detectors (Dosunmu *et al*, 2004). Therefore, it is clear that for CMOS circuits, the most preferred semiconductor material is Ge as P-MOSFETs and N-MOSFETs as well as in photonic modules for electronic-photonic integrated circuits respectively. Kamata (2008) reports that Ge as a channel material will achieve higher drive currents and higher switching speeds. From Table 2.2 ideally, Ge has the highest hole mobility when compared to other possible channel materials like the III-V compounds, whereas these materials have received considerable attention as promising materials due to their high electron mobility. Similarly the lattice constant of Ge is almost equal to that of GaAs. Consequently it is possible to consider a stack for future metal-oxide semiconductor where germanium-on-insulator(GOI) substrate is introduced on Si or by direct growth of Ge on a Si substrate. This substrate can be used to grow III-V materials with matching lattice parameter such as GaAs (Haynes *et al*. 2006). Though III-V semiconductor materials are excellent candidates for use as channel materials in CMOS due to their better mobility, less effective mass as compared to silicon, yet there is significant disparity between electron and hole mobilities (i.e. electron mobility being several times higher than hole mobility), with III-V technology not compatible with silicon .Thus, it is unlikely that a future CMOS technology will involve co-integration of germanium-based P MOS and III-V based N MOS device (Schmid *et al*. 2015; Goley and Mantu, 2014). However, an all Ge solution would be preferable for ease of process. Metal electrodes are used to replace high purity polycrystalline silicon which is widely employed in silicon CMOS technology because of the following reasons: Firstly, Fermi level pinning of the polycrystalline silicon-high-K interface can cause high threshold voltage and instability (Hartmann *et al*. 2007). Secondly, the polycrystalline silicon- high-K gate stack exhibits strong remote phonon scattering and degrades the channel mobility (Fischetti *et al*. 2001). Finally the use of metal gate eliminates the depletion capacitance in the polycrystalline silicon electrodes (Robertson and Wallace, 2015). Using metal electrodes, high-K materials on Ge is an attractive approach to scale an electronic device and improve the performance of future applications of CMOS technology. Direct deposition of high-K material on germanium will exhibit a low quality interface associated with a high density of surface states between high-K gate oxide material and germanium substrate which severely restrains the application of high performance Ge MOSFETs. For this reason, germanium oxide GeO_2 , is used as an interfacial layer similar to SiO_2 in silicon CMOS. This oxide permits a greater physical thickness of dielectric material between the gate and channel without sacrificing gate capacitance. Oxides with physical thickness less than 2 nm exhibit an unacceptable large gate leakage current leading to excessive power lost (Goley and Mantu, 2014). The gate capacitance is written as (Kumar, 2012):

$$C = \frac{\varepsilon_o \kappa \mathrm{A}}{t_{ox}} \tag{10}$$

where A is the area, κ is the dielectric constant, ε_o is the permittivity of free space, t_{ox} and is the oxide thickness. This relation motivates the implementation of high-K materials into gate stacks. The only way to increase capacitance C, when t_{ox} cannot be reduced further is to increase κ (assuming A is fixed). Meanwhile, germanium as a material has been widely employed in current silicon CMOS manufacturing. For example, germanium based CMOS circuits i.e. germanium on insulator fully depleted MOSFETs have been demonstrated (Wu *et al*. 2014) and they have also demonstrated that an I_{on}/I_{off} current ratio greater than 10^5 indicates that germanium does have the potential to replace silicon as channel material beyond the 10 nm node. Promising results in the development of germanium MOSFETs have been obtained but major obstacles remain (Claeys and Simoen, 2007). A full CMOS compatible P MOSFET process was implemented with $\mathrm{H}f0_2/T_iN$ gate stacks (Deleonibus,2007).Similarly, technologies in the fabrication of thin high-K gate dielectric materials such as germanium oxynitride (GeON) or zirconium oxide ($Zr0_2$) for germanium have been presented (Chui *et al*. 2002; Shang *et al*. 2004). Chui *et al*. (2002) have successfully developed Ge MOSFET having zirconium oxide gate dielectric with an equivalent oxide thickness of $6-10\ \overset{0}{A}$, that showed relatively good MOSFET material with high mobility.

CONCLUSION

The physical properties of single crystal germanium and germanium based devices have been reviewed in this article. Most of the work on material growth and device development has been done by using MBE and MOCVD techniques. Germanium based devices are realized as potential candidates in photonics. Germanium as light source emit at 1550 nm wavelength and high performance photodetectors, modulators, waveguides and other components have been demonstrated. There are still so many areas of application of this important semiconductor material particularly now at the nanoscale. Germanium is also useful as a gamma-ray detector.

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