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Development from PIN to GaAs Based MISFET Photo-Detector: *A Review*

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Abstract: High speed photo-detector are a key building block, which allow a large bandwidth upto several GHz for telecommunication application such as local area network, long distance communication upto several kilometers without signal degradation with high switching speed and high quantum efficiency. In this review paper, the recent progress in development and integration of Ge photo-detector on Si based photonics will be comprehensively reviewed along with a proposed structure of GaAs MISFET photo-detector for future research trends.

Index Terms: PIN , MESFET,MISFET Photodetector

1. Introduction

As the data rate approaches 10 Gb/s metal interconnection like copper wire is facing a number of issue such as slow resistance-capacitance limits speed and large heat dissipation, under these condition, it is well known that for data rate above 10Gb/s optical signal is more advantageous compared to conventional copper wire interconnections. As a result combining sophistical process techniques, low cost, mass production, high data rate Si and III-V compound semiconductor based electro photonic integrated circuit emerge as one of the most promising solution for the next generation interconnection techniques. In fact long haul communications have been based on fiber optic techniques for the last 35 years. The wavelength used for long distance communication is mainly 1310 nm and 1550 nm range because of minimum loss in silica fiber at this window. If the same wavelength is utilized for short distance communication like FTTH, FTTC etc all end user will be able to connect directly to the external servers without the need of any MODEMs making global communication easier and cheaper. However BSNL introduces FTTH and FTTC technology before approx 5 years in western and southern region.

Now a days enormous effort have been invested in Si, and GaAs photonic techniques and critical break throughs and milestones have been achieved, various passive components [1], active device like LASER [2] and high speed modulators [3] have been reported. The device at the end of optical path is photo detectors which converts optical signal into electrical signal are vital component for Si photonic integrated circuits. In Past decade Si Photonics upsurge was the first successful demonstration of high efficiency germanium photodetector [4]. Although Si photo detectors have been widely used in optical receivers in the wavelength around 850 nm for multimode optical communication in broadband, its relatively large bandgap of 1.12 eV corresponding to an absorption cutoff wavelength of ~ 1.1 µm hiders Si photodetectors application in longer wave length range of 1310 nm and 1550 nm. For a seamless integration with current long-haul communication technology, a material with strong absorption coefficient in the 1310 & 1550 nm is very desirable.

Among the variable choices, III-V compound semiconductor posses the advantage of high absorption coefficient, high carrier drift velocity and mature design and fabrication technology for optical devices, as proposed GaAs MISFET structure in this paper which will work upto several Ghz operating frequency. Although, integration of high performance III-V photodetector onto the Si Plate form by flip-chip bonding or direct heteroepitaxy has been widely reported.

In this review paper, we first introduce section 2&3 different photo detector structure and light coupling schemes respectively. In section 4 historical research trend of Ge photodetector reported by various research group, In section 5 Proposed structure and conclusion has been presented.

2. Photo detector Structures

There is a number of Ge based photodetectors are reported. Brief descriptions of some well known photodetector structures are described here.

2.1. PIN Photo Detectors

PN junctions are one of the most commonly used configurations for semiconductor photodetectors. The PIN diode where "I" stands for intrinsic, includes an intrinsic region in between the P and N regions. Because of built-in potential or external reverse bias, the intrinsic region is depleted and has high resistivity, so that the voltage drop takes place mainly in this region, giving rise to high electric fields for effective collection of photo-generated electron-hole pairs (EHP). In this configuration, the thickness of the intrinsic region is always many times larger than the highly-doped regions so that most of the EHP's are generated within the intrinsic region where the strong electric field helps to sweep the EHP to the adjacent p+/n+ region faster than diffusion. Another advantage of the PIN structure is that the depletion-region thickness (the intrinsic layer) can be tailored to optimize both the quantum efficiency and response bandwidth. In Ge PIN photodetectors, while the photo absorption intrinsic layer is usually Ge for effective absorption around 1550 nm , the p+ and n+ region can be formed either by implantation [5] or *in-situ* doping to form p+ and n+ regions for the PIN structure [6]. Another way is to use p+/n+ single crystalline Si substrates or deposited polycrystalline Si heterojunctions [7].

2.2. Metal-Semiconductor-Metal (MSM) photo Detectors

PIN photodiodes produce a voltage drop across the diode terminals in response to an external optical input. Such devices are categorized as photovoltaic devices. On the other hand, MSM photodetectors are photoconductive devices whose conductivity is altered when an optical illumination is imposed. Therefore, MSM photodetectors are only functional under non-zero external bias. MSM photodetectors possess the advantage of low capacitance and relative ease of fabrication. The intrinsically low capacitance resulting from its configuration has always been utilized to fabricate high-speed large area detectors. One issue in early Ge MSM photodetectors was their high dark current density, which gives rise to high stand-by power consumption, thus making Ge MSM photodetectors unfavorable and impractical. Due to the narrow bandgap and strong Fermi-level pinning of the metal/Ge interface at valence band, hole injection over Schottky Barrier Height (SBH) is the major component of the dark current in Ge MSM detectors. Regarding this issue, application of dopant segregation (DS) to Ge MSM photodetectors for dark current suppression was experimentally demonstrated by Zang *et al.* [8-10]. Metal-Ge Schottky barrier height modification by an intermediate layer of large bandgap material such as amorphous Ge and SiC is also proposed [11]. While the demonstrated Ge MSM detectors are able to achieve dark current suppression of two to four orders of magnitude, it is still an open question whether these MSM Ge photodetectors are competitive with PIN devices.

2.*3. Avalanche Photo Diode*

The simplest avalanche photodiode (APD) has a similar device structure to a p-i-n photodiode. However, a voltage close to its breakdown is usually applied to APD for detection of low power signal with high sensitivity. Under sufficiently higher external bias, electrical field in the photodiode's depletion region becomes high enough to initiate impact ionization which is responsible for carrier multiplication. Therefore, one absorbed incoming photon does not only generate one electron/hole pair but rather a large number of EPHs leading to a quantum efficiency potentially large than unity. The most important performance indices for APD is excess noise factor quantified by effective ratio of electron and hole ionization rate (k_{ff}), gain-efficiency product and sensitivity.

2.4. Dark Current Criteria for Photodetectors

An important issue in integrated photodetectors is dark current, which increases the power consumption of the receiver. Most importantly, shot noise associated with this leakage current undesirably degrades the Signal-to-Noise Ratio (SNR) leading to increased bit error rates (BERs). Generally, dark currents less than 1 µA are referred to as acceptable value for a high-speed receiver design, below which the transimpedance amplifier (TIA) noise is the main noise source [12,13,14]. In practice, a precise value of the required dark current depends upon the speed of operation and the amplifier design. In the recent successful demonstration of an Ge-on-Si photodetector-based receiver, photodetectors with dark current of both ~10 nA [13] and ~2 µA [15] were reported. Depending on the receiver design, a higher dark current level is tolerable with certain sacrifices in the receiver parameters. For example, Vivien *et al.* [16] have shown that with an increase of the input power of about 20% in comparison with photodetector without dark current, a photodetector with 300 µA dark current is still able to ensure a BER of 10^{-18} at a frequency close to 50 GHz.

3. Ge Photodetector Light Coupling Schemes

3.1. Normal Incidence Photodetectors and the Bandwidth-Efficiency Tradeoff

Due to its low process complexity, Normal Incidence photodetectors are widely used in communication technologies. However, they suffer from an inherent drawback due to the bandwidth-efficiency tradeoff. This tradeoff results from the opposite requirement of the thickness of the photo-absorption layer for high bandwidth and high efficiency [17]. The carrier-transit-time-limiting bandwidth f_t can be expressed as [18]:

$$f_t \approx 0.45 \text{ x } (v/d)$$

While the ideal efficiency η assuming zero reflection and full carrier collection is:

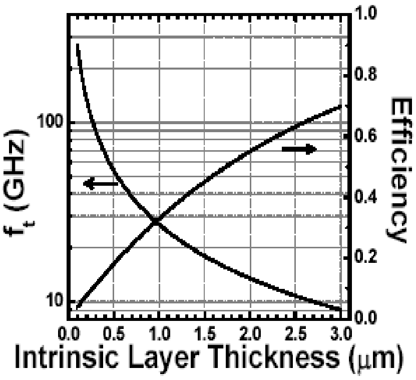

Figure 1: *A Calculated carrier-transit-time-limiting bandwidth and efficiencies of normal incidence PIN Ge photodetector.*

$$\eta \approx 1- e^{-\alpha \text{ x } d}$$

where v is carrier transit velocity, d is intrinsic region's thickness and α is material's absorption coefficient. Using v = 6 × 10 ^{6} cm/s for Ge and α = 4,000 cm^{-1} the carrier-transit-time-limiting bandwidth and efficiencies *versus* intrinsic region thickness can be plotted as **Fig. 1**. As can be seen for a Ge device with 3dB bandwidth of 100 GHz, an intrinsic layer thinner than 0.27 µm is required with a resulting efficiency of ~10%.

3.2. Resonant Cavity Enhanced (RCE) Detectors

To overcome the tradeoff between bandwidth and efficiency in NI detectors, one method is to sandwich a thin layer of photo absorbing material between two light reflectors as shown in **Fig.2** so that cavity resonance is enhanced [19,20]. In this structure, light is ideally trapped between the two reflectors and travels through the center light absorber multiple times until fully absorbed. At the same time, the photo absorption layer can be thin enough to achieve high bandwidth. Another advantage of RCE detectors is the wavelength selectivity. When the light reflector is fabricated in the form of a Bragg reflector, only light in a small range of certain wavelengths is reflected effectively so as to produce high efficiency. The RCE device's light selectivity makes it especially useful for wavelength division multiplexing (WDM) systems.

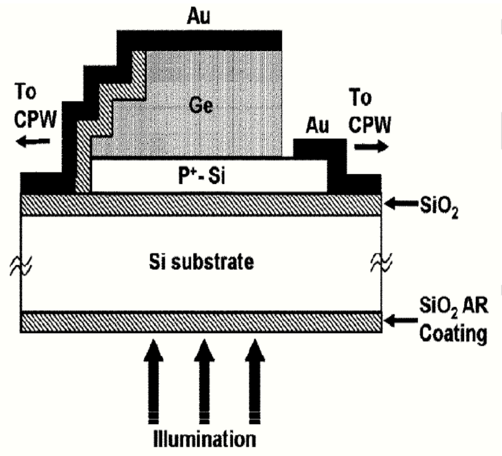

Figure 2: Cross-sectional view of the back-illuminated Ge-SOI Schottky photodetector. From [19].

3.3. Waveguide Photodetectors

Waveguide integrated photodetectors have been considered to be one of the most promising candidates for overcoming the bandwidth-efficiency tradeoff in normal incidence detectors. In this configuration, a light signal is delivered to the device by in-plane optical waveguide rather than top down, permitting the bandwidth and efficiency to be determined almost independently because the efficiency is specified no longer by the photo absorption layer thickness, but rather by the waveguide length. Furthermore, large scale integration of Si optical and electrical devices requires all devices to be fabricated on the same planar wafer, which makes an optical waveguide indispensable. Thus integration of a waveguide with photodetectors seems to be a natural choice. The development of Ge-on-Si photodetectors has been going on for more than ten years.

4. Research Trends in Ge Photodetectors

In this section various historical research are found and described here

4.1. Normal Incidence to Waveguide Integration

Ge-on-Si photodetector development for Si photonics applications normal incidence Ge photodetectors were first fabricated as shown in **Fig.3** and comprehensively studied [4,6,21,22,23,7,24, 25] due to their ease of processing Due to the bandwidth-efficiency tradeoff, typical NI incidence Ge photodetectors offer moderate quantum efficiencies and bandwidths.

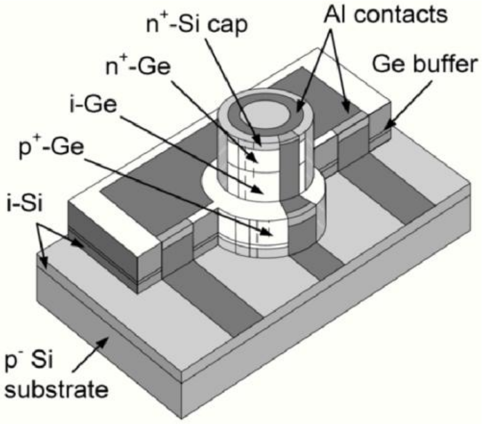

Figure 3: 3D view of the PIN Ge photodiode with 49 GHz bandwidth. From [24].

4.2. Improvement of Speed Performance of Waveguide Ge Photodetectors

Another trend of the continuous evolvement of Ge photodetectors is the increase of detector bandwidth. At the starting point of Ge detectors' integration with Si waveguides, Ge growth on SOI wafers and optical coupling between Ge detectors and Si optical waveguides was first explored. The reported detectors are ~100 µm long to ensure full absorption of light around 1550 nm wavelength, inevitably leading to large device capacitance so that the bandwidth are limited <10 GHz by RC delay.

4.3. Zero-Bias PIN Photodiode

Because of high dark current in PIN diode it consumes high standby power and degraded signal to noise ratio. Moreover, it is desirable for the detector and the receiver circuit to operate on a single power supply which restrict bias voltage less than 1.5 V [26]. As a result, there has been an increasing research interest in the development of low-bias or even zero bias PIN photodiodes.

4.4. Avalanche Photodetectors

Avalanche photodetectors offers much lower signal-to-noise ratio compared to PIN or MSM structures. Therefore more and more interest is being focused on Ge-based avalanche photodetectors. Recently, Intel [25], IBM [28] and IME [27] have all reported successful fabrication of such devices. The first Ge-based APD was demonstrated by Kang *et al* [25]. In this device separate-absorption-charge-multiplication (SACM) configuration is used to take advantage of both Si's low noise property and Ge's strong absorption near 1550 nm wavelength. The device exhibits low excess noise. The reported sensitivity of - 28 dBm at 10 Gb/s is equivalent to a commercial III-V APD.

4.5. Pursuit of Higher Bandwidth

Now a days Ge photodetector bandwidth reaches to 50Ghz and can be used as 40Gbps system. On the other hand in correspondence with III-V photodetectors, there are much place to reaserch. For bandwidth beyond 100 GHz, much thinner Ge intrinsic layers should be used. As a result In high frequency region high parasitic effect such as contact resistance, stray capacitance and inductance may become the main limiting factors in bandwidth performance. To overcome these effect the mushroom-mesa structure [17] (**Fig. 4**) may be of help for further bandwidth evolution, since it is capable of reducing the Rs and capacitance simultaneously.

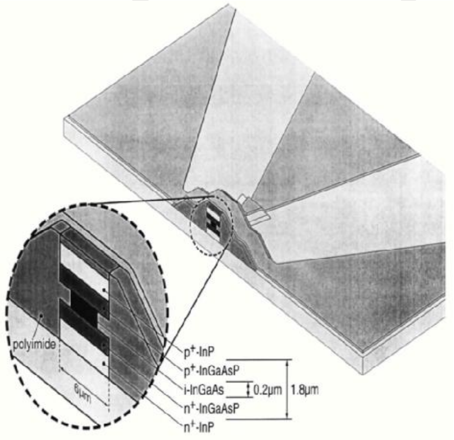

Figure 4: *Schematic view of III-V photodetector based on mushroom structure.*

5. Proposed III-V compound semiconductor GaAs- MISFET Photdetector Structure

The bipolar phototransistor used for optical detection provides not only high gain due to transistor action but also provides lower signal to noise generation as compared to APD. However, fabrication of bipolar transistor is more complicated than that of photodiode and the inherent large capacitance associated with base collector junction degrades its high frequency performance. A unipolar transistor which can provide sufficient gain and very good high frequency response is the GaAs MESFET. The first high speed optical detector using GaAs MESFET was proposed by Baak[30] way back in 1997. in comparison with the fastest known APD the GaAs MESFET seems to be advantageous for the dispersion measurements on optical fibres with high speed and low dispersion. Such a device also called as optical controlled GaAs MESFET or simply GaAs OPFET in literature[31]. Although, in principle, both the Si and GaAs MESFET can be used as photodetector but the later one is considered to be the better choice due to its higher mobility, better optoelectronic properties due to its direct band gap properties of GaAs and better microwave characteristics.

Therefore GaAs based devices, e.g. GaAs MESFET's are widely used for high speed circuit applications. However Gate current of the schottky contact become appreciable for the forward bias of several tenths of a volt which severely limits on maximum drain current, the noise margin and flexibility of the circuit design. The Gate insulating layer can improve those drawbacks. GaAs MISFET's with different approaches in pursuit of gate insulating layers and structures. The lack of reliable thin oxide layers especially to native oxide limits the development of the GaAs MOSFET's. The SiO_2 films were successfully deposited onto n-GaAs substrates by Photo-chemical-vapour deposition (Photo-CVT)using deuterium(D_2) lamp as the excitation source[32].

In view of above mentioned advantage of GaAs MISFET in comparison to GaAs MESFET we propose to simulate,The Photodetector structure similar to that reported by Jau-Yi Wu et al [29]. The structure under consideration for simulation in Figure 5. In which light is absorbed in GaAs based channel region. Metal electrode and oxide works as window and channel region where incident light is absorbed.

Device Structure:

The structure shown below the thickness of undoped GaAs is 5000 Å. Channel layer is n-type GaAs with doping concentration of $N_d=5x10^{16}$ cm^{-3} with thickness of 2000A [29].The chosen oxide region is SiO_2. The device parameter is given below

Gate length =2µm
$Nd=5x10^{16}$ $/cm^3$
Oxide thickness = 1000Å
Channel thickness =2000Å
Thickness of buffer layer=5000Å

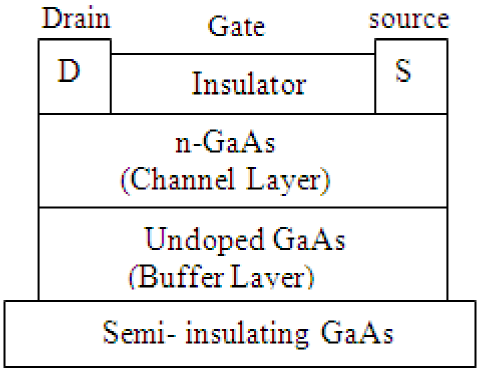

Fig.5: Schematic cross sectional view of the n- channel depletion mode MISFET

For GaAs material

Electron affinity= 4.07 eV
Energy band gap=1.424 eV
Intrinsic concentration=2.1 x $10^6/cm^3$
Mobility of electron = 5000 $cm^2/V\text{-}s$
Mobility of Holes=285 $cm^2/V\text{-}s$

Conclusion:

As above Brief Discussion made on various photodetector and comparison done. It is found that Ge or Si type Photodetector limits the operating frequency upto 50 Ghz . Phototransistor devices like MESFET have leakage gate current of shottky contact appreciable for forward bias of several tenths of a volt which severely limits on maximum drain current. The proposed device have gate insulating layer which overcome the gate current.

The device may be used for different wavelength detection at 1310 nm or 1550 nm by changing the active layer of MISFET.

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