NOVEL DESIGNS, MATERIALS AND TECHNIQUES IN PLASMA BIPOLAR JUNCTION TRANSISTOR (PBJT) FABRICATION AND TESTING

BY

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THESIS

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ABSTRACT

Improvements in the fabrication and testing of PBJTs by making adjustments that seek to enhance yield and PBJT operation have been performed. Results were observed to be consistent with those previously obtained by other techniques. The collector plasma generated was analyzed using a Princeton Instruments PI-MAX 3 intensified charge-coupled device (ICCD) camera. As a further improvement on the PBJT design, fabrication using a novel laterally-doped configuration is underway and initial work in making this device has been illustrated. Finally, the fabrication of PBJTs on a silicon carbide substrate has been proposed and thoroughly looked into with possible applications as a high-power phototransistor. Preliminary work on these robust silicon carbide PBJT devices has been expounded upon.
To my parents
ACKNOWLEDGMENTS

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CHAPTER 1

INTRODUCTION

A completely new approach to transistor fabrication is to couple an electron-hole plasma (EHP) with an electron-ion plasma (EIP), which exist in the solid state and the gas phase respectively. In the semiconductor industry, plasma is often used in etching and deposition but it has not been incorporated into state-of-the-art electronic devices. Gas-phase materials were not even used as a component-part in modern microelectronic fabrication until 2010 when Intel and Micron realized that air gaps could be used as part of the low-k dielectric stack in the interconnect of their 25 nm multi-level cells 64 Gbit NAND flash memory [1]. A new type of transistor presented in this work, the plasma bipolar junction transistor (PBJT), which integrates an electron-ion plasma into solid state electronics, is achieved by replacing the collector of an $n\!p\!n$ bipolar junction transistor with a low temperature gas-phase plasma.

It must be noted that gas-phase plasmas were used in devices such as voltage regulators, switches, modulators and alphanumeric displays earlier in the 20th century but the 1960s to 70s saw the rise of solid-state devices. The similarities in characteristics and physical properties of semiconductor and gas-phase plasmas were, in fact, well known by solid-state electronics innovators. Bardeen and Brattain used the kinetic theory of gas phase plasma when analyzing some important transistor parameters [2]. Subsequently, Shockley pointed out that the germanium filaments in the germanium transistor performed the same function as tubes in gas discharge electronics [3] but the fields of semiconductors and gas-phase plasmas have however followed generally different paths ever since then.

The increasing development of plasma physics on its own in the fifties and sixties was motivated by research directed to get controlled thermonuclear fusion and magnetohydrodynamic conversion of thermal energy to electrical energy [4]. However, in the nineties, plasmas on a smaller scale, referred to as microplasma, were demonstrated. Photodetection in the visible spectrum using a DC operated silicon microplasma device was achieved in 2002 [5]. Three years later, a detailed measurement of the photosensitivity of
pyramidal microplasma arrays in silicon was done [6], providing an explanation of a plasma-semiconductor interface in terms of energy band diagrams. After another three years, a hybrid plasma/semiconductor transistor with an external emitter was demonstrated for the first time [7]. The very first plasma bipolar junction transistor was however not demonstrated until 2010 [1].
CHAPTER 2

THEORETICAL BACKGROUND

2.1 Bipolar Junction Transistors

A bipolar transistor can simply be thought of as a transistor made up of two $pn$ junctions. The main idea behind a bipolar junction transistor is that one can simply bring the $pn$ junctions close enough to each other such that the electrons from the forward biased junction are injected into the base of the transistor. The electron then diffuses through the base and into the collector before recombining. This idea is a fundamental transistor principle found by Bardeen and Brattain [2].

The band structure of a bipolar junction transistor with its three regions - emitter, base and collector - is shown in Figure 2.1. The voltages $V_{ext}^e$ and $V_{ext}^c$ are the emitter-base and collector-base voltages. The terms $E^e_n$ and $E^p_n$ in the figure are representations for the quasi-Fermi levels of the electrons and holes respectively.

![Energy band diagram of bipolar transistor under normal bias](image)

Figure 2.1: Energy band diagram of bipolar transistor under normal bias [8].
To allow for transistor operation, diffusion current must be transported from one $n$-type region to another. Therefore, the base must be short enough compared to the diffusion length of the minority carriers (electrons) in the region. The electron concentration of the transistor at any point $z$ (at either the $n$-side or $p$-side) on the band diagram is given in the equation 2.1 below and expressions for integration constants $C_1$ and $C_2$ can be determined from this [8]. Consequently, expressions for the collector and emitter currents can then be determined. To start with, the expression for the electron concentration is:

$$n(z) = C_1 e^{z/L_n} + C_2 e^{-z/L_n} + C_3$$ \hspace{1cm} (2.1)

where $L_n$ is the diffusion length. Based on the band diagram shown earlier, at the emitter base borderline $l_p^e$, we have:

$$n(l_p^e) = n_{base} e^{qV_{ext}^e/kT}$$ \hspace{1cm} (2.2)

where the equilibrium concentration of electrons in the base is denoted by $n_{base}$. Also, the external voltage and depletion width have a subscript $e$ representing the emitter.

Another boundary condition can be obtained from the requirement that $C_3$ be equal to the equilibrium electron concentration at the $p$-side ($C_3 = n_{base}$). A third boundary condition comes from the electron concentration at the collector base junction $l_p^c$. The standard transistor theory inserts, for the change $\Delta n$ from the equilibrium $V_{ext}^c = 0$ concentration, an expression given by:

$$\Delta n(l_p^c) = n_{base} (e^{qV_{ext}^c/kT} - 1)$$ \hspace{1cm} (2.3)

This is the true value only if no carriers are injected from the emitter, and the collector diode is essentially independent [8]. If one puts $n(l_p^e) = 0$, chooses $l_p^e$ as the zero of the coordinate system (i.e., $l_p^e = 0$), and denotes $l_p^c$ as the voltage-dependent base width $W_b$, then
\[ \Delta n(0) = n_{\text{base}}(e^{\frac{qV_{\text{ext}}}{kT}} - 1) = C_1 + C_2 \]  
(2.4)

and

\[ C_1 e^{W_b/L_n} = -C_2 e^{-W_b/L_n} \]  
(2.5)

which gives:

\[ C_1 = \frac{n_{\text{base}}(e^{\frac{qV_{\text{ext}}}{kT}} - 1)}{e^{2W_b/L_n} - 1} \]  
(2.6)

and

\[ C_2 = \frac{n_{\text{base}}(e^{\frac{qV_{\text{ext}}}{kT}} - 1)}{1 - e^{2W_b/L_n}} \]  
(2.7)

By inserting the equations for \( C_1 \) and \( C_2 \) above into the equation 2.1 for \( n(z) \) and integrating over the generation/recombination rate \( U_s \) as in the equation,

\[ \int_{-\alpha}^{-l_p} eU_s dz = \frac{eL_n n(-\alpha)}{\tau_n} (e^{V_{\text{ext}} - 1}(1 - e^{-\alpha + l_p})) \]  
(2.8)

the emitter current contribution can be calculated. It must be mentioned that the condition \( W_b \ll L_\alpha \) is essential for transistors because the electrons need to be injected into the collector without much recombination in the base. As a result, the emitter diode functions are independent of the collector. However, the collector current density can be increased. The increase as a result of emitter injection can be calculated by assuming that the additional collector current density \( j_c \) is a diffusion current at \( z = W_b \) giving:

\[ j_c = -eD_n \frac{dn(z)}{dz} \bigg|_{W_b} \]  
(2.9)

The term \( n(z) \) can then be obtained. Besides, from \( C_1 \) and \( C_2 \), it is observed that the collector current density is controlled by the emitter voltage, i.e.:
Consequently, for an arbitrary bipolar transistor, the collector current $I_c$ can be represented by the function:

$$I_c = -I_{CO} \left( e^{\frac{qV_{ce}}{kT}} - 1 \right) + \alpha_N I_E$$  \hspace{1cm} (2.11)

where $\alpha_N$ is a transfer coefficient, and $I_{CO}$ is the reverse saturation current of the collector. In addition, one can interchange the emitter and collector and then obtain the emitter current:

$$I_E = -I_{EO} \left( e^{\frac{qV_{ce}}{kT}} - 1 \right) + \alpha_I I_C$$  \hspace{1cm} (2.12)

The coefficient $\alpha_I$ is used and the subscript $I$ stands for ‘inverted’ because, in the normal operation, electrons are not transferred from collector to emitter. The above equations for $I_c$ and $I_E$ along Kirchhoff’s law given by the base current representation

$$I_B = I_E + I_C$$  \hspace{1cm} (2.13)

give what is known as the Ebers-Moll equation. These equations give us a good and simple model that retains much of the physics behind the operation of a bipolar transistor. The four constants $\alpha_N, \alpha_I, I_{EO},$ and $I_{CO}$ can be determined by experiments for any given transistor.

Furthermore, the common emitter current gain, denoted by $\beta$, and the common base current gain, denoted by $\alpha$, are important figures of merit for a transistor. These gains characterize the operation of a bipolar junction transistor when it is in a “forward-active” mode. Transistors must be engineered to give high values of common emitter current gain in order to achieve proper amplification. This common emitter current gain can be represented as:
while the common base current gain can be represented as:

\[ \alpha = \frac{I_C}{I_E} \]  

(2.15)

The two gains are related by:

\[ \beta = \frac{\alpha}{1 - \alpha} \]  

(2.16)

For a simple bipolar transistor with a uniformly doped emitter, base, and collector regions, if the generation/recombination, high current effects and other 2-D effects are ignored, the transistor is considered ideal and the common emitter current gain can be represented as:

\[ \beta = \frac{N_E D_B L_E}{D_E N_B W} \]  

(2.17)

where \( D \) is the diffusivity of the minority carrier in the subscript region, \( N \) is the doping concentration of the subscript region, \( L_E \) is the characteristic diffusion length of the minority carriers in the emitter, and \( W \) is the non-depleted base width. Since it is typically advantageous to have large gains in bipolar transistors, \( N_E \) is usually engineered to be much larger than \( N_B \), and \( W \) is kept as small as possible, such that the base resistance is not too large and the base is not completely depleted during normal operation. However, if the concentration is non-uniform in the base, then:

\[ \beta = \frac{N_E D_B L_E}{D_E G_B} \]  

(2.18)

where \( G_B \) is the Gummel number of the base and represents the total integrated base charge. It is given by:
Finally, the important second-order effects that affect transistor operation like the Early (base width modulation) and Kirk (base push out) effects are well explained in the literature [9]. The Kirk effect, in particular, typically occurs when the density of minority carriers injected in the base collector depletion region, $J_C$, becomes similar to the doping level of the collector. That is, when:

$$J_C \frac{1}{qv_{sat}} \approx N_C$$

(2.20)

where $N_C$ is the collector doping concentration and $v_{sat}$ is the saturation velocity of the base minority carriers.

2.2 Plasma

Plasma can be thought of as an electrically energized matter in a gaseous state [10]. The three components of plasma are: electrically neutral gas molecules; charged particles in the form of positive ions, negative ions and electrons; and photons. The gas molecules present are either in the ground state or excited state. While the negative ions present carry only one charge, the positive ions can have more than one. In this work, the plasma generated was caused by an electric discharge in a gas; however, there are other ways of generating plasma. These include but are not limited to the heating of matter to very high temperatures and also by laser radiation. Another way to describe plasma is as a hot, ionized and quasi-neutral gas. Ionization fractions become significant at fractions of $10^{-5}$ to $10^{-3}$ parts ionized as a gas temperature is raised to a few tenths of its ionization potential [11].

Langmuir coined the term ‘plasma’ in 1928 [12]. He was studying electric discharges in mercury vapor at low pressure and concluded that he was dealing with a particular state of matter, like Crooke had earlier concluded [13], when he noticed that the ionized gas, forming a
cold luminous column in a long glass tube, had uniform electric and optical properties along its entire length.

Plasma physics has applications in select chemical processes. For example, corona discharges can be used to improve the properties of oils and also for water purification by ozone production from oxygen [14]. Also, the atomic hydrogen created in hot torch discharges has applications in welding and cutting. Furthermore, plasma can be used as the gain medium in a gas laser. Finally, the ionosphere is a weak plasma, so communication without a satellite is possible between distant locations as observed in radio broadcasting.

2.2.1 Debye Length

The Debye length is a very important characteristic of a plasma. Assuming the charged particles present in the plasma in the form of positive ions and electrons are in equal and large numbers and occupy a volume of plasma of \( \lambda^3 \) where \( \lambda \) is the mean free path, then at low electron and ion temperatures, practically random motion occurs. However, at finite temperatures, equipartition of energy results in the electrons possessing higher speeds. They occupy areas around the ions and form a covering (negative charge) subject to fluctuations, as individual electrons come in and out of these areas. The electrons are said to ‘screen’ the positive charge, such that an applied electric field exerts a smaller force on the ions compared to when this screen is absent. The once uniformly distributed electron space charge is redistributed such that its time average is more concentrated around the positive charges, locally changing the field and the potential as a result. At finite distances \( r \) and assuming other charges are absent, the Coulomb potential of a single unscreened charge \( \theta \) can be represented as:

\[
V(r) = \frac{e}{4\pi\varepsilon_0 r}
\] (2.21)

However, if a space charge, \( \rho_{\text{net}} \), is present, one has to solve Poisson’s equation to obtain the potential of a screened charge. Assuming a spherical geometry, we have:
Assume an ion temperature of $T$ and an electron temperature $T_e >> T$: If $r$ is small, the potential approaches equation 2.22, but if it is large, the potential approaches 0. If the average of $\rho_{net}$ in the plasma is taken over the entire volume, a value of zero is obtained, that is, $(N^+)_0 = (N_e)_0$. However, around a positive ion at $r = 0$, for a constant density of positives and a Boltzmann distribution of electrons, we get:

$$\rho_{net} = \rho^+ - \rho_e = (eN^+)_0 - (eN)_0 \exp(eV/kT_e)$$

The exponential indicates that $N_e (V)$ is as a result of competition between the electron kinetic and potential energies. For smaller values of $eV/kT_e$, we get:

$$\rho_{net} = (eN_e)_0 [1 - \exp(-eV/kT_e)] \approx \frac{eV}{kT_e} (eN_e)_0$$

By substituting the term above for $-\frac{\rho_{net}}{\varepsilon_0}$ in equation 2.22, we get:

$$\frac{1}{r^2} \frac{d}{dr} \left( r^2 \frac{dV}{dr} \right) = \left[ \frac{e^2(N_e)_0}{kT_e \varepsilon_0} \right] V$$

$$\left[ \frac{e^2(N_e)_0}{kT_e \varepsilon_0} \right]$$ is the inverse square of a characteristic distance or screening radius, $\Lambda$. For $(N_e)_0 = N_e$ the term is represented as:

$$\Lambda = \frac{kT_e \varepsilon_0}{e^2(N_e)} \approx 70 \left( \frac{T_e (K)}{N_e (m^{-3})} \right)^{1/2}$$

This characteristic distance is the Debye length. For example, for $kT_e = 1 \text{ eV}$ and $N_e = 1 \times 10^6 \text{ m}^{-3}$ at a screening distance $\Lambda$, the potential is $1/\theta$ of the Coulomb potential and $\Lambda \approx 7 \times \ldots$
The resulting differential equation has a solution of the form $e^{-r/r}$ and the screened potential is:

$$V(r) = A \frac{e}{r} \exp(-r/A)$$  \hspace{1cm} (2.27)

By comparing this with the equation $V = e/4\pi \varepsilon_0 r$ (equation 2.21), one can see that the exponential term describes the electron screening effect of the ion, responsible for the quick fall of $V$ with increasing $r$ [10]. As a result, most of the field lines of a central positive charge terminate in the electronegative charges around it and only a small fraction of them go further than the Debye length.

Finally, although the bulk plasma is typically quasi-neutral, the introduction of an external electric field results in a charge separation in the bulk plasma because the lighter electrons respond to the electric field quicker than the heavier ions. However, in order to preserve the neutrality of the plasma, an ambipolar electric field is created such that the charges are restored back to their initial position. The plasma frequency that occurs as a result of oscillations due to this charge separation and restoration by the ambipolar electric field is given by [15]:

$$\omega = \sqrt{\frac{n_p e^2}{M \varepsilon_0}}$$  \hspace{1cm} (2.28)

where $M$ is the mass of the electron.

2.2.2 Plasma Sheath

The sheath of a plasma is a region of non-neutral potential that occurs between the plasma and the wall. The rest of the plasma is typically quasi-neutral. A transition layer (much wider than the sheath and with a finite electric field) that occurs between the non-neutral sheath and the quasi-neutral plasma is called the presheath. The presence of the presheath region is
necessary in order to maintain the ion flux in a plasma. The ion-velocity at the plasma sheath edge is referred to as the Bohm velocity of a plasma. This velocity can be represented as:

\[ u_B = \sqrt{\frac{eT_e}{M}} \]  

(2.29)

The sheath region of a plasma is similar in electric field to a reverse-biased npn BJT. The diagram in Figure 2.2 describes the plasma sheath and shows how its potential, electron/ ion density and length scale compares with the bulk plasma and the presheath. At the operating pressures and voltages of the PBJT, the collisions that occur within the plasma sheath are very important and can lead to the sheath thickness being tens to hundreds of times greater than the plasma Debye length.
Figure 2.2: Plot of electric potential of sheath and presheath regions near the wall. The sheath edge is at $x = 0$. It is the boundary between the quasi-neutral presheath and the positively charged sheath [16], [17].
CHAPTER 3

DEVICE FABRICATION

The PBJT was fabricated on epitaxial silicon wafers. These wafers had a [100] orientation, which possesses [111] planes that slope upwards from the plane of the surface at 54.74°, unlike a [110] orientation, which is characterized by vertical {111} walls [18]. A schematic representation of the PBJT is shown in Figure 3.1. An epitaxial layer with thickness varying from 5 to 15 µm served as the $p$-type base of the PBJT as seen in Figure 3.1. This $p$-type base layer had a doping of $7 \times 10^{15}$ cm$^{-3}$ while the emitter substrate was $n$-type with a doping of $1 \times 10^{19}$ cm$^{-3}$. A voltage (HV) of up to 405 V was applied in generating the plasma for the PBJT in this thesis.

![Diagram of PBJT device schematic](image)

Figure 3.1: PBJT device schematic [19].
The energy band diagram of a PBJT is shown in Figure 3.2. The plasma replaces the $n$-type collector of a typical $nnp$ BJT. The sheath of the plasma is similar to the depletion region at the base-collector interface of the $nnp$ BJT.

![Energy Band Diagram](image)

Figure 3.2: Simple PBJT energy level diagram [19].

For transistor operation to occur, as explained in detail in the theoretical background, the base must be short enough to ensure that electrons can diffuse through it. However, it must be thick enough such that the extension of the base-collector depletion region into the emitter-base depletion region is effectively avoided [17]. This is a phenomenon known as punch-through-breakdown, that is, the space-charge layer extends completely across the base region. This process effectively eliminates the base region and transistor action ceases as a result.
An example of a typical device is shown in Figure 3.3. The molybdenum anode has been placed over a $\rho$-type silicon base surface. By performing a preferential crystallographic anisotropic potassium hydroxide (KOH) etch, a circular $\rho$-type mesa with a 54.74° slope was obtained on the [100] epitaxial wafer. An alpha step IQ profilometer with a 5 µm tip was used to verify the etch-depth accuracy. Buffered oxide etch was then done to remove a previously deposited silicon nitride (Si$_3$N$_4$) masking layer. This was followed by a subsequent RCA clean which is a standard set of steps for removing organic (by SC-1 clean) and ionic (by SC-2 clean) contaminants with a hydrofluoric acid (HF) etch done after the SC-1 and before the SC-2 to remove the built-up oxide layer. In order to prevent plasma discharge in unwanted areas, the entire wafer except the base surface, was covered in plasma-enhanced chemical vapor deposition (PECVD) deposited silicon nitride (Si$_3$N$_4$), which served as a passivation layer.
Previous devices similar to this [20] were tested by first placing a fluted tube over a silicon base surface. In these cases, the anode was placed over the base surface before sealing the fluted tube. The device was vacuum-sealed by using a vacuum-grade epoxy, as seen in Figure 3.4, to attach the fluted tube placed carefully over the anode and base surface. The base and emitter contact windows are left exposed for testing probes. A wire from the anode passes through the epoxy and goes directly under the fluted tube for testing purposes. After the epoxy is dried, the top of the fluted tube is connected to a turbomolecular-pumped vacuum system, which is used to take the device to vacuum pressure. The required gas for plasma generation is then put into the chamber. One problem with this technique however is that, although the native oxide (which forms when silicon is exposed to air) is etched away before the fluted tubes are placed over the device, a significant amount of oxide is yet again formed in the process of placing a fluted tube over the device and attaching this tube into place. Sealing the tube into place involves placing the device over a hot plate with the base surface completely exposed to air. The device is usually placed on a hot plate in order to allow for the epoxy to completely cure before the device is taken to vacuum pressure for testing. Besides, sealing smaller devices with this technique represented a significant challenge and required a degree of practice and expertise.

![Fluted-tube PBJT sealing and testing method.](image-url)
As an improvement on this method, all testing done for this thesis was carried out by first placing the device on a piece of glass and then inserting it directly into a vacuum chamber as seen in Figure 3.5 above. Enamed copper wires were first attached to the base and emitter contacts. This was done carefully under a microscope. A conductive epoxy was used for the attachment of these wires to their appropriate contact points. This was followed by the application of a non-conductive epoxy over the conductive epoxy such that a plasma discharge is avoided at these connection points. The molybdenum anode with an enameled copper wire attached to it was placed over the silicon base surface at a distance to ensure operation in the vicinity of the pd minimum. After the wires have been attached and before the device is placed in the vacuum chamber, a native oxide etch is performed with hydrofluoric acid-to-water ratio of 50:1. Another set of wires are present in the vacuum system that run from the inside of the chamber, through feed-throughs, and to the outer part of the chamber. An electrical contact is made with these other wires and then the chamber is closed.
Figure 3.6: PBJT device with copper wires attached to base and emitter contact points.

This new design, shown in Figures 3.5 and 3.6, makes it easy to test smaller devices as long as thinner enameled copper wires are used. Furthermore, the design also makes it possible for devices, which do not get damaged during operation, to be re-used at a future date. Another native etch is however required before a device can be re-used due to the built up native oxide that grows once the device is taken out of vacuum. In previous devices, once the fluted tube is removed from its connection to the vacuum system, the silicon is exposed to air and as a result of the non-removable nature of the vacuum-grade epoxy used in attaching the tubes to the base/emitter portion, these devices cannot be re-used. Moreover, this new method opens up the possibility of varying the gap distance between the anode and the base surface and allows for investigating what effect changes in gap distance will have on the operation of a particular device.

For most of the work done on this thesis, molybdenum, which is a hard and heavy metal, was used as the anode of the transistor. Using a hard metal like molybdenum as opposed to a lighter one like aluminum reduces the possibility of oxidation from the little leftover oxygen in the chamber. Other hard materials like tungsten and platinum can be used as well. Table 3.1 shows some physical properties of anode materials that were looked into in selecting the anode for the PBJT.
Table 3.1: PBJT anode materials and their physical properties.

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (g. cm(^{-3}))</th>
<th>Atomic Mass (g)</th>
<th>Atomic Number (g. mol(^{-1}))</th>
<th>Electronegativity (Pauling Scale)</th>
<th>First Ionization Energies (KJ. mol(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum (Al)</td>
<td>2.7</td>
<td>27</td>
<td>13</td>
<td>1.61</td>
<td>577.5</td>
</tr>
<tr>
<td>Molybdenum (Mb)</td>
<td>10.28</td>
<td>96</td>
<td>42</td>
<td>2.16</td>
<td>684.3</td>
</tr>
<tr>
<td>Tungsten (W)</td>
<td>19.25</td>
<td>183.84</td>
<td>74</td>
<td>2.36</td>
<td>770</td>
</tr>
<tr>
<td>Platinum (Pt)</td>
<td>21.45</td>
<td>195.1</td>
<td>78</td>
<td>2.28</td>
<td>870</td>
</tr>
</tbody>
</table>

For all the required lithography in the fabrication of the PBJT, an EV Group 420 Double Side H-Line Mask Aligner was used at a wavelength of 405 nm. SPR 220 was used as the photoresist and AP 8000 was used as the adhesion promoter. At the conclusion of the fabrication process, a K and S 708 Dicing Saw with Nickel dicing blades acquired from advanced dicing technologies was used in dicing the wafer into individual dies as seen in Figure 3.7.

Figure 3.7: Some samples after dicing.
Proper metal deposition is crucial in the fabrication of these devices as contact points need to be provided from the p and the n layers of each individual device on the wafer to the base and emitter contact windows respectively. An AJA ATC ORION 8 HV series sputtering system with eight 2-inch magnetron-sputtering sources and timing chimneys designed to optimize deposition was used in depositing the metal stack. This particular sputtering system is equipped with two 750 W DC power supplies and has deposition uniformity within +/- 5 % over the four-inch samples that were used in the PBJT fabrication. Titanium, chrome, nickel and gold served as the ohmic contact and were deposited with thicknesses of 50 nm, 30 nm, 10 nm and 30 nm respectively. Also, as an improvement on previous devices, an additional thin layer of chrome was deposited after the Ti/Cr/Ni/Au metal stack had been deposited. This was done to help with a subsequent silicon nitride (Si$_3$N$_4$) deposition step.

In addition, sputtering was used instead of evaporation as the metal deposition method because, after some trials, it was observed to provide a better adhesion. As explained in the introduction to this thesis, the deposition process is one example of a process in conventional semiconductor processing in which plasma is used, and sputtering is a good example of a deposition method that utilizes plasma in its operation. During sputtering, in order to get the disc of material to be deposited to a high negative potential, it is bombarded with positive argon ions created in a glow discharge. The target material is sputtered as neutral atoms by momentum transfer and ejected surface atoms are condensed onto the substrate placed on the anode.

The source is not heated to high temperature during ion bombardment. Also, the vapor pressure of the source is not a consideration as it is in evaporation. The amount of material, $W$, sputtered from the cathode is inversely proportional to the gas pressure, $P_T$, and the anode-cathode distance, $d$, as represented by:

$$W = \frac{kVi}{P_Td}$$  \hspace{1cm} (3.1)

where $V$ is the working voltage, $I$ the discharge current and $k$ the constant of proportionality.

The sputter yield, that is, the number of atoms removed per incident ion, is a function of the bombarding species, the ion energy of the bombarding species, the target materials, the incident angle of the bombarding species, and its electronic charge. The deposition rate is
proportional to the yield for a given plasma energy. Table 3.2 shows the sputter yield for metals that were used in making the ohmic contact for the PBJT.

Table 3.2: Sputter yields of metals used as ohmic contact in PBJT fabrication [21].

<table>
<thead>
<tr>
<th>Metal</th>
<th>Sputter Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chrome (Cr)</td>
<td>1.18</td>
</tr>
<tr>
<td>Gold (Au)</td>
<td>2.40</td>
</tr>
<tr>
<td>Nickel (Ni)</td>
<td>1.33</td>
</tr>
<tr>
<td>Titanium (Ti)</td>
<td>0.51</td>
</tr>
</tbody>
</table>

Above all, it must be mentioned that the PBJTs, due to the damage of the base surface, fail after a few minutes to two hours of operation [20]. The use of square-cut molybdenum metal pieces over the silicon base in generating the plasma is a configuration that has been found to prolong the device lifetime compared to situations where a single thin wire was used as the anode [17]. In the case of a thin-wire-anode, it was observed that a corona discharge forms but this corona transitions into a glow discharge, establishing transistor operation [20]. If a single wire is used, then the electric field, characteristic of a corona, is strongest at the anode. The glow discharge (which a corona transitions into in the case of a thin wire but is present throughout a molybdenum square anode configuration) is what liberates electrons into the plasma from the $p$-type silicon base.
4.1 Electrical Testing

The PBJT was tested in a common-emitter configuration with base resistance, \( R_B = 10 \, \Omega \), and collector resistance, \( R_C \), varied from 240 k\( \Omega \) to 720 k\( \Omega \). Tektronix probes were utilized to measure to voltages at both ends of \( R_C \). The common-emitter configuration for testing the PBJT is shown in Figure 4.1. The output was recorded using a National Instruments NI-6211 USB DAQ on a LabVIEW interface and the acquired data for a simple device is shown in Figure 4.2.
Figure 4.2: Collector voltage, base current and base-emitter voltage as a function of time.
However, a plot of the base current $I_B$ vs. collector voltage $V_{ce}$ is a good way to demonstrate the transistor action of the PBJT and is shown in Figure 4.3 for $V_{ce}$ ranging from 365 V to 405 V at a neon gas pressure of 15 Torr.

![Graph showing base current vs. collector voltage](image)

Figure 4.3: Collector voltage vs. base current ($V_{ce}$ vs. $I_B$) with $V_{ce}$ ranging from 365 V to 405 V.

The hysteretic behavior observed is a characteristic that was also observed in previous PBJT tests [17], [20], [22]. It can be seen that as the high voltage is gradually increased as shown in the graph, the base current required in reaching saturation decreases significantly. This hysteretic behavior can also be observed in the plots of collector voltage versus base current (Figure 4.4) and collector current versus base current (Figure 4.5).
Figure 4.4: Collector voltage vs. base current operating pressures ranging from 10 Torr to 40 Torr.

Figure 4.5: Collector current vs. base current for $V_{cc}$ ranging from 365 V to 405 V.
4.2 Optical Imaging of Plasma

A gated intensified charge coupled device (ICCD) was used to image the collector plasma. This PIMAX-3 device was placed parallel to the base surface and triggered by a 100 Hz, 0.7 V RMS sinusoidal voltage. Figure 4.6 is an example of the plasma image from a device operation. All observations are explained in the next section.

Figure 4.6: PBJT WinView interface showing false color image of plasma generated between the molybdenum anode and the $\rho$-type silicon base surface in a typical device. (Parameters: Gap Distance = 2 mm, Pressure = 25 Torr, epitaxial layer thickness = 15 µm and device radius = 3 mm.)
4.3 Observations and Discussion

Overall, the phenomena observed in the optical imaging of the collector plasma were consistent with similar work previously done on the PBJT [20]. As seen in the Figure 4.6 above, the top part is the molybdenum anode while the bottom is the cathode. Figure 4.6 is an example of the device in forward bias and at maximum intensity. In reverse bias, the intensity was observed to decrease steadily until the end of the cycle. For further understanding of the behavior of the interaction of the plasma with the base surface, attempts were made to further image the spikes observed in the collector voltage as seen in Figure 4.2. The problem is that, with this new configuration, the spikes sometimes seemed to vary in amplitude from cycle to cycle. Another challenge encountered was that, during the imaging of the collector plasma, another plasma sometimes formed on metallic portions of the chamber even though such parts were well-covered in glass as seen in Figure 3.5. With these two issues, most of the ICCD imaging data acquired were, to an extent, unreliable for further analysis.

One way to solve the problem of unwanted plasma generation that was encountered is to attempt to test the PBJT with a vacuum chamber that has no inner metallic part, thus avoiding plasma generation in unwanted parts that may affect imaging results. Furthermore, the author sometimes observed an expansion in the plasma volume during operation of the device. One way to solve this problem and get better results is to attempt to confine the plasma by completely surrounding the base surface with a glass piece. Although this will improve the reliability of the transistor, it may pose a challenge for imaging and further study of the PBJT’s plasma-surface interaction. Another way to confine the plasma is by fabricating the PBJT in a laterally-doped configuration as explained in section 6.2 and shown in Figure 6.1. This design confines the plasma well and prevents expansion of the plasma volume during operation.
CHAPTER 5

SILICON CARBIDE PBJT DEVICES

5.1 Introduction

The PBJT has potential new applications in various areas. One application is to use it as a high-power phototransistor. For a conventional transistor, during amplification, most of the power is deposited at the collector, resulting in device breakdown. However, the use of a plasma collector enables the device to withstand hundreds of volts or more depending on the material used for the $p\!n$ junction cathode. A more robust material such as silicon carbide (SiC) was thus thought of as a good idea for further improvement. This chapter focuses on the fabrication of PBJTs using a new material, silicon carbide.

Silicon has been the main material in semiconductor micro-fabrication and power applications over the last quarter of a century due to its constantly advancing processing techniques. However, a wide bandgap material, silicon carbide (SiC), because of its electrical and physical properties, is increasingly gaining attention as an alternative. The advantages of SiC include: high thermal conductivity, high breakdown electric field, and saturated carrier velocity. In addition, there have also been recent improvements in the production of silicon carbide wafers of high quality. In fact, high-power SiC devices like diodes and transistors have already been shown and SiC Schottky diodes are readily available for 600 V and 1200 V from Cree Inc. The ability to perform high power switching due to its low specific on-resistance is an important advantage of the SiC BJT [23]. These characteristics could be advantageous to the SiC PBJT as well. Although the SiC PBJTs have not been fabricated as of this writing, the rest of this chapter explains methods of fabrication of the SiC PBJT, possible challenges and a few important parameters that need to be taken into consideration in the design of these transistors.

Finally, forming good ohmic contacts to both $n$-type and $p$-type SiC would be crucial to the functioning of a SiC PBJT, as it is for those already fabricated on epitaxial silicon wafers.
Various methods do exist in the literature that have been utilized successfully for silicon carbide [23].

5.2 Electrical properties

The characteristic wide bandgap and high breakdown electric field are important electrical properties of silicon carbide.

Wide bandgap

When electrons in the valence band of a semiconductor are excited with an external energy that is equal to its bandgap, they can move to the conduction band. At a given temperature, the external energy creates an intrinsic equilibrium electron-hole pair (EHP) concentration. This concentration depends on the bandgap exponentially. However, the EHP concentration becomes equal to the doping concentration at the intrinsic temperature and this typically affects device operation. The intrinsic temperature depends on doping concentration and is about 150 °C for Si. The bandgap is 2.4 eV for 3C-SiC, 3 eV for 6H-SiC and 3.2 eV for 4H-SiC. However, that of Si is only 1.1 eV. Because of its large bandgap, SiC has an intrinsic temperature of up to 1000 °C, and hence advantageous for high temperature applications.

High breakdown electric field

Because their wide bandgap leads to high impact ionization energy, wide bandgap materials typically have a high breakdown electric field. For SiC, the high critical field is about 2 MV/cm, about 10 times higher than in Si. The breakdown voltage of a $pnn$ diode is given by

$$V_B = \frac{E_c W}{2} \tag{5.1}$$

where $V_B$ represents the breakdown voltage, $E_c$ is the critical field and $W$ represents the width of the drift region. In SiC, a significantly higher breakdown voltage can be achieved with the same drift region than in the case Si. Also, a smaller drift region can be achieved in SiC for the same breakdown voltage. Because of its higher electric breakdown field, higher doping levels $N_D$ of the drift region can be used in SiC [24].
\[ N_D = \frac{2eV_B}{qW^2} = \frac{\varepsilon E_0^2}{2qV_B} \] (5.2)

One can calculate the specific on-resistance \( R_{on-sp} \) of the drift region by using the equation:

\[ R_{on-sp} = \frac{W}{q\lambda_n N_D} = \frac{4V_B^2}{\epsilon\mu_n E_C^3} \] (5.3)

In theory, this on-resistance, in the case of a SiC high voltage device, is about 1000 times lower than that of Si. As a result of this, there is a lower on-state power loss because of the effect it has on the forward voltage drop.

### 5.3 Mobility, Recombination and Energy Gap Narrowing

**Mobility**

The carrier mobility of SiC is given by the Arora model [25]. In 6H-SiC, the mobility is observed to be more anisotropic compared to 4H-SiC. One can observe that the low electric field mobility depends on both the doping level and temperature and it is given by:

\[ \mu_{n,p} = \mu_{n,p,min} \left( \frac{T}{300} \right)^{\alpha_{n,p}} + \frac{\mu_{n,p,max}}{1 + \left( \frac{N_D + N_A}{N_{n,p,ref}} \right) \left( \frac{T}{300} \right)^{\alpha_{n,p}}} \] (5.4)

The Caughey-Thomas model gives the high-field velocity [26]. The carrier drift velocity \( (v_D) \) saturates at high fields due to an increase of the optical phonon scattering and reaches the saturation velocity \( (v_{sat}) \). The high-field mobility depends on this saturation velocity as well as other parameters and is given by:

\[ \mu_{n,p}(E) = \frac{\mu_{n,p}^0}{1 + \left( \frac{\mu_{n,p}^0 E}{v_{sat}} \right)^{1/\beta}} \] (5.5)
The electron density and the hole density are equal in an intrinsic semiconductor. The mass-action law gives this intrinsic-carrier density as:

\[ n_i^2 = N_c N_v \exp \left[ \frac{-(E_c - E_v)}{kT} \right] = N_c N_v \exp \left[ \frac{-E_g}{kT} \right] \] (5.6)

\( E_g \) represents the bandgap energy. Also, \( N_c \) and \( N_v \) represent the effective density of states in the conduction and valence band, respectively. \( n_i \) is observed to be constant and independent of the Fermi energy for any given semiconductor at a fixed temperature.

**Recombination**

The Shockley-Read-Hall (SRH) equation describes carrier recombination and is represented as:

\[ R_{SRH} = \frac{np - n_i^2}{\tau_p (n + n_i e^{E_{trap}/kT}) + \tau_n (p + n_i e^{-E_{trap}/kT})} \] (5.7)

where \( \tau_n \) and \( \tau_p \) represent the respective electron and hole lifetimes respectively, which depend on factors like temperature and dopant’s type and concentration. These lifetimes may vary from 0.1 \( \mu \)s to 2 \( \mu \)s in 4H-SiC epitaxial layers [27]. Auger recombination on the other hand occurs when an electron and a hole recombine in a band-to-band transition, and the resulting energy is transferred to another electron or hole. It is represented as:

\[ R_{Auger} = (C_n n + C_p p)(np - n_i^2) \] (5.8)

where \( C_n \) is \( 5 \times 10^{-31} \) cm\(^{-6}\)s\(^{-1}\) and \( C_p \) is \( 2 \times 10^{-31} \) cm\(^{-6}\)s\(^{-1}\) [28], [29].

**Energy Gap narrowing**

A significant reduction of the bandgap typically occurs as a result of the free carrier’s high concentration. At high doping levels, carrier-carrier interaction, carrier-impurity interaction and
overlap of the electron wave functions cannot be ignored. For an *n*-type material, the band-edge displacements are represented as:

$$\Delta E_c = A_{nc} \left( \frac{N_D}{10^{18}} \right)^{1/3} + B_{nc} \left( \frac{N_D}{10^{18}} \right)^{1/2} \text{(eV)}$$

$$\Delta E_v = A_{nv} \left( \frac{N_D}{10^{18}} \right)^{1/4} + B_{nv} \left( \frac{N_D}{10^{18}} \right)^{1/2} \text{(eV)}$$

where the parameters are listed in Table 5.1. Bandgap narrowing has to be taken into consideration in bipolar transistors because it increases the minority carrier concentration in the emitter and the emitter efficiency is reduced as a result of this.

Table 5.1: Band-edge displacement parameters for 4H-SiC and 6H-SiC [30].

<table>
<thead>
<tr>
<th><em>n</em>-type</th>
<th>$A_{nc}$</th>
<th>$B_{nc}$</th>
<th>$A_{nv}$</th>
<th>$B_{nv}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4H-SiC</td>
<td>-1.5 x 10^{-2}</td>
<td>-2.93 x 10^{-3}</td>
<td>1.9 x 10^{-2}</td>
<td>8.74 x 10^{-3}</td>
</tr>
<tr>
<td>6H-SiC</td>
<td>-1.12 x 10^{-2}</td>
<td>-1.01 x 10^{-3}</td>
<td>2.11 x 10^{-2}</td>
<td>1.73 x 10^{-3}</td>
</tr>
</tbody>
</table>

5.4 Etching

The etching of silicon carbide poses a significant challenge because of the strong chemical bond that exists between Si and C. Etching with reasonably good etch rates has however been demonstrated with equipment at this institution with reasonable etch rates of up to 0.8 µm min^{-1} using titanium/nickel as a mask [31].
5.5 Challenges: Micropipes and Sputtering

A micropipe defect is an example of a defect that occurs commonly in silicon carbide. It refers to a crystallographic defect in a single crystal substrate. Micropipes are formed when a screw dislocation propagates through the bulk of a sample during the wafer growth process. If present in high density, it may become a problem for a SiC PBJT operation. The term *screw dislocation*, as mentioned earlier, refers to a type of dislocation that transforms successive atomic planes in a crystal into the shape of a helix as seen in Figure 5.1. Temperature and impurities are factors that affect micropipe formation. However, in 2007, Cree Inc. claimed to have manufactured 100 mm (4-inch wafers), zero-micropipe, $n$-type SiC substrates.

![Figure 5.1: Typical micropipe defects in silicon carbide compared to a smaller carrot defect [23].](image)

Figure 5.1: Typical micropipe defects in silicon carbide compared to a smaller carrot defect [23].
The author also suspects that the sputtering of silicon carbide may represent a significant challenge and looked into sputtering rates of Si compared to SiC. SiC was observed to have a higher sputtering yield compared to silicon for neon gas [32].
CHAPTER 6

CONCLUSION AND FUTURE WORK

6.1 Conclusion

A new type of transistor, the plasma bipolar junction transistor, has been presented. Improvements on the fabrication and testing methods have been explained, compared to previous generations of the device and results acquired have been shown. The new methods of testing presented in this work open up the possibility of further investigation of how changes in gap distance affect the performance of the transistor for a particular device. Furthermore, silicon carbide PBJTs have been thoroughly explained as capable of serving as high-power phototransistors. However, areas where the device could still be improved upon are in terms of its lifetime and scalability. Unlike conventional transistors, the anode, which is essential in generating gas-phase plasma that serves as the collector, has to be integrated manually in the design used for this thesis. Consequently, a step forward would be to integrate the collector anode at wafer level. This new design will allow for significant downscaling and also for the improvement in device lifetime. Research on a new method of fabrication is already in place and significant progress has been made in the fabrication of these devices on silicon-on-insulator (SOI) wafers as explained in the next section.

6.2 Future Work

6.2.1 Laterally-doped PBJTs

A schematic of the new PBJT design that allows for anode integration into the solid-state portion of the device and, consequently, reduction of the plasma volume is shown in Figure 6.1. This new design allows for the creation of PBJT arrays, which could have more applications,
compared to the previous PBJT designs. Consequently, the PBJT could then be used as a component of microplasma devices.

Figure 6.1: Laterally-doped PBJT cross-section [33].

These novel laterally-doped PBJT devices are being fabricated on the device layer of SOI wafers. An SOI wafer comprises a silicon device layer (ρ-type in this case), an oxide layer and a handle layer. For the fabrication in progress of these new devices, wafers with device layers ranging from 45 µm up to 80 µm, oxide layers of up to 2 µm, and handle layers of up to 350 µm as acquired from Ultrasil Corporation are in use. These SOI wafers have a \(<100\) orientation and a resistivity of 1-10 Ω.cm.

The main idea behind this new device design is to create the \(n^+\) type collector and emitter by lateral diffusion as represented in Figure 6.1. To begin with, alignment marks are placed on the SOI wafers. Next, an inductively coupled plasma reactive ion etching (ICP-RIE) is done to etch the trenches for diffusion. Then, a diffusion (\(n\)-type) with phosphorus is done into these trenches (to create the emitter and the collector).
To carry out the diffusion, a predeposition is first done in a tube furnace, and then a drive in is done in an annealing chamber at temperatures up to 1200 °C for a time frame of about 18 hours to allow the dopants to go well into the wafer and achieve desired doping thicknesses. For conventional diffusion, machines used for ion implantation are typically used for diffusion as well; however, the method whereby an annealing chamber is used after a predeposition process, as used for these laterally-doped PBJTs, works well for research projects. So far, in the fabrication of these devices, it has been discovered that SiO$_2$ with melting points of up to 1725 °C serve as better diffusion masks than PECVD-deposited nitride (Si$_3$N$_4$) which was observed to be unable to withstand the required high doping temperatures. After the diffusion is done, the emitter base and collector contact points are opened for metallization. Finally, a plasma trench etch is done. It is in this trench that the plasma for the PBJT is generated.

6.2.2 Black-silicon PBJTs

Devices with the base silicon interface modified into a black-silicon surface with nanocone-structures have been proven to work in collaboration with another group on campus. The use of a PBJT with a black-silicon base surface increases surface field emission and facilitates breakdown. These devices, unlike the conventional PBJT, have applications as burst-mode transistors because of the various modes observed in their operation [20]. Further work can be done in fabricating these devices to significantly improve their operation and also in seeking to optimize their use as a special kind of transistor.
REFERENCES


