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The Role of Bipolar Junction Transistors (BJT) in Audio Signal Amplification for Bluetooth Speaker

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ABSTRACT

The development of Bluetooth technology has helped drive advancements in wireless audio devices, particularly in Bluetooth speakers. The Bipolar Junction Transistor (BJT) has become an important component as an audio signal amplifier. This article discusses the role of BJT in strengthening weak audio signals into loud and clear sounds. The study in this article reviews the characteristics, working mechanisms, as well as the advantages and disadvantages of BJTs using the commonly used NPN common emitter configuration. In addition, this article also discusses the thermal response of BJTs and the influence of temperature on their performance, as well as the fabrication process of Germanium-on-Insulator (GeOI) as an alternative to improve BJT performance. The results show that BJTs have good signal amplification capabilities but are vulnerable to high temperatures.

1. INTRODUCTION

In recent decades, we have witnessed continuous advancements in technology, particularly in the field of electronics. Each year brings updates to general technology standards and new solutions introduced to the public as consumers. This has led to the widespread adoption of technologies such as Bluetooth, which implements the Internet of Things (IoT) and is rapidly developing in daily life, as stated by Dachyar et al. (2019). Bluetooth is a standard for short-range radio frequency communication that allows devices to connect and exchange information over short distances (Padgette et al., 2017). With the progress of automation and electronic information technologies, wireless control technologies like Bluetooth have been extensively applied in various devices (Zhang M. A, 2025). Bluetooth was first developed by Ericsson in 1994 as a short-range wireless communication technology to replace cables. In 1998, the Bluetooth Special Interest Group (SIG) was formed by Ericsson, IBM, Intel, Nokia, and Toshiba (Junjie Yin et al., 2019). Its low cost and favorable specifications have led to the increasing use of Bluetooth in various fields, especially in consumer electronic devices, such as Bluetooth speakers (Yin et al., 2019).

In the development of Bluetooth speakers, traditional speakers initially relied on cables to connect from one device to another. Due to limitations and quality concerns, Bluetooth was introduced as a solution to enable wireless connectivity between devices and speakers. This advancement would not have been possible without key components that allow speakers to receive audio signals from other devices—such as smartphones, laptops, or tablets—while maintaining clear sound output (Muraleedhara et al., 2024).

BJT is a semiconductor component made from Silicon (Si) and Germanium (Ge) that helps the BJT to easily integrate well with other components due to its semiconductor properties. Here, the BJT acts as an audio signal amplifier that ensures the sound from the speaker remains clear, thus preserving the quality of Bluetooth speakers. An amplifier is an electronic device that increases the strength of a signal. An audio amplifier is an electrical circuit that produces louder sounds. This is done by drawing energy from the power supply and controlling the output to match the shape of the input signal but with a larger amplitude. An amplifier can also be seen as a simple box or block that contains amplifying devices, such as transistors (Tuwaidan et al., 2015). BJT is a component in the Bluetooth speaker circuit as an audio signal amplifier; if BJT was not there as an audio signal amplifier, the sound produced by the speaker would be less clear and quieter.

This review article aims to discuss the role and function of BJT components by exploring their characteristics, specifications, and internal structures. The author hopes this discussion will broaden understanding of the crucial role that BJTs play as semiconductor components in amplifying audio signals in everyday products like Bluetooth speakers.

2. MATERIALS

2.1 Bipolar Junction Transistor (BJT) Composition

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Transistors are grouped based on their constituent semiconductor materials, namely silicon and germanium and based on the application of the transistor designed, namely as a signal amplifier, switch, high voltage, or small signal Handoko, et al (2017). The selection of semiconductor materials cannot be separated from their physical properties, where semiconductors are a type of material with electrical conductivity that is between a conductor and an insulator, and has an energy gap of less than 6 eV^2. This characteristic allows semiconductors to act as conductors at room temperature, but change into insulators when at very low temperatures. This behavior is greatly influenced by the energy band structure in the semiconductor material itself (Akhadi, 2015). Changes in these characteristics are greatly influenced by the energy band structure in the semiconductor material.

According to (Mujadi, 2018), the use of semiconductor materials can be found in several electronic devices in everyday life because of their electrical conductivity properties which can change when injected with other materials (doping), including germanium. The development of germanium utilization has begun to experience significant progress since the discovery of the theory of semiconductors, especially in its application to various electronic devices. This discovery encouraged efforts to simplify electronic components that were previously large and complex to become smaller, lighter, more practical, and affordable. This development began with the presence of diode components, which are semiconductors consisting of two layers, namely P and N types, made from germanium and silicon crystals. Diodes made from germanium have a lower forward voltage compared to silicon diodes, even though both have four valence electrons. This difference occurs because germanium atoms are larger than silicon, so the number of electrons is also greater. As a result, the electric current flowing through the germanium diode tends to be greater, allowing this device to operate at a lower voltage. In addition, germanium also has higher conductivity, so that current can flow more easily. However, silicon is superior in terms of heat resistance, so in practice, many semiconductor diodes are more often made using silicon because it is more stable when used at high temperatures (Rusly, 2024).

2.2 Classification and Characteristic

The BJT type itself consists of two types, namely NPN type bipolar transistors and PNP type (Handoko, et al 2015). PNP transistors are marked with an arrow symbol pointing inward, namely from the Collector terminal to the Base terminal. Conversely, NPN transistors have an arrow on the Emitter leg pointing outward. NPN type BJT transistors will start to function if there is a minimum voltage of around 0.7 Volts between the Base and Emitter terminals. While in PNP transistors, this voltage is needed between the Collector and Base terminals. In operation, the electric current in NPN transistors flows from the Collector to the Emitter, while in PNP transistors the current flows from the Emitter to the Collector. The difference in the direction of the arrow on the Emitter leg is an easy way to distinguish between the two PNP transistors that have an inward arrow, while NPN transistors have an outward arrow (Arkan et al., 2024).

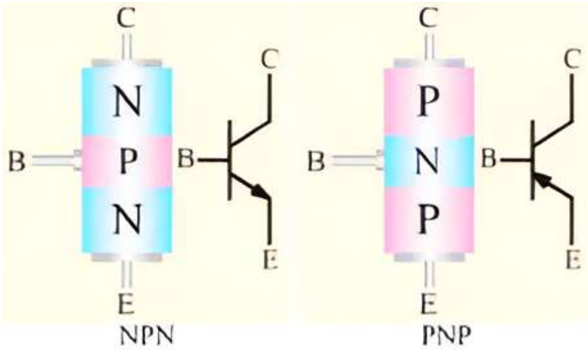

Figure 1. Conventional Symbol of BJT

Source: Adapted from Maftunzada, S. (2023).

Structurally, BJT has three main regions, namely base, collector, and emitter, where the base is responsible for activating the transistor, the collector functions as the positive pole, and the emitter as the negative pole. The electric current or signal flowing in the BJT passes through these three regions, and the characteristics of the flow are influenced by the properties and composition of the semiconductor material used (Aseeri, A. H., & Ali, F. R. (2018).

The transistor symbol is shown in figure 2.2 of the journal, where in an NPN transistor, the arrow on the emitter points outward, indicating current flowing out of the emitter, while in a PNP transistor, the arrow points inward, indicating current flowing into the emitter. This arrow represents the direction of conventional current (from positive to negative) at the base-emitter junction: in an NPN transistor, conventional current flows from the base (positive) to the emitter (negative), so the arrow points out of the emitter, reflecting the flow of electrons from the emitter to the base (since electrons carry negative charge and move in the opposite direction of conventional current); whereas in a PNP transistor, conventional current flows from the emitter (positive) to the base (negative), so the arrow points into the emitter, reflecting the flow of holes from the emitter to the base (Maftunzada, 2023).

2.3 Characteristics of BJT

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Transistors act as current regulators, allowing a small current to control a larger current. The amount of current allowed between the collector and the emitter is primarily determined by the amount of current that flows between the base and the emitter. (Maftunzada, 2023). The physical implementations of integrated BJT devices are lateral and vertical structures. Lateral BJTs suffers from beta roll off effect at high and low collector current situation. The current gain decays with low collector current physically originates from the surface combination of these surface carriers of the base node of BJT.

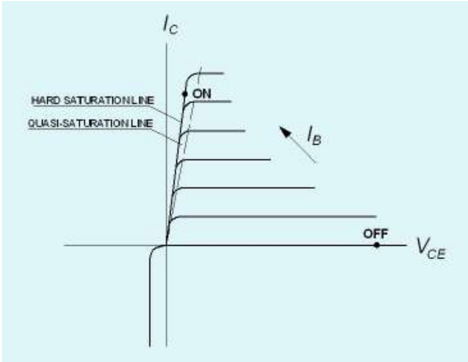

Figure 2. Voltage-current characteristics of the BJT

Source : Adapted from Li et al., (2020).

2.4 Characteristics of NPN

To flow current in an NPN transistor requires a positive (+) source connection on the base leg. How NPN works is when the voltage hits the base leg, up to the saturation point, it will induce current from the collector leg to the emitter. And the transistor will be logic 1 (active). And if the current through the base decreases, the current flowing from the collector to the emitter will decrease, up to the cut-off point (Husain, 2022). In NPN type transistors, there is a different direction of current flow than in PNP type transistors, where NPN flows current from collector to emitter. And in NPN, to flow the current, a connection to a positive (+) source is required at the base of the leg. The way NPN works is when the voltage that hits the base leg, to the saturation point, will induce current from the collector leg to the emitter. And the transistor will be logic 1 (active). And if the current through the base decreases, then the current flowing from the collector to the emitter will decrease, to the cutoff point. This decrease is very fast because the comparison of the withdrawal that occurs between the base and collector exceeds 200 times (Wildan, 2019)

2.5 Characteristics of PNP

In a PNP BJT, holes are injected from the emitter into the n-type base under forward bias and are collected by the collector under reverse bias. The base current (ib) is small compared to the emitter current (ie) because most of the current consists of hole flow. The base current arises mainly from three mechanisms: (1) recombination of injected holes with electrons in the base, (2) electron injection from the base to the emitter, and (3) electron generation from the collector to the base, which reduces ib. Recombination is the dominant contributor to base current. BJTs are widely used as amplifiers and switches because the collector (ic) and emitter currents can be controlled by the base current. The emitter current consists of both hole and electron currents, while the collector current primarily consists of holes that travel through the base without recombination (Ahn, 2022).

3. MECHANISM

3.1 Bluetooth Mechanism

Bluetooth provides a working mechanism by creating a wireless network in close proximity, operating on the same channel and frequency to connect with each other (Muraleedhara et. al, 2024).

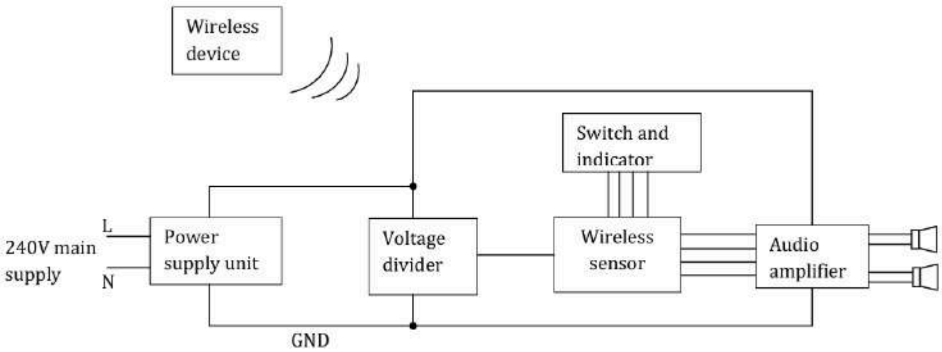

Figure 3. The mechanism of Bluetooth speaker receiving signals

Source: Amewornu, E. M. (2015)

In the mechanism of how Bluetooth speakers can receive signals from sources such as phones, laptops, etc., as shown in figure 3.1, there are certainly stages that are directly involved with the components present in the Bluetooth speaker. This mechanism begins with the speaker receiving power from an electrical source (outlet) of 240V AC through a cable. This will generate electric current that will pass through the power supply unit (PSU) to convert and reduce the AC (alternating current) voltage into a lower DC (direct current) voltage. This DC voltage will then be divided according to the power requirements of each component through a voltage divider. When we press the power button, the system will certainly activate and the indicator light will turn on. Bluetooth will start searching for signals within the closest range and will receive signals from devices such as mobile phones. This digital signal is then converted into a weak analog audio signal which is sent to the audio amplifier (as a speaker) and will draw power from the PSU to strengthen the audio signal, which will ultimately be emitted from the speaker. This mechanism is supported by a ground (GND) system that will control the flow of electricity to remain stable. This wireless sensor component is a device that can detect the connected Bluetooth distance with a switching mode, where when the device moves away from the speaker, the audio signal will be detected as moving away by this device and will immediately lose the audio signal within a distance of up to 1 meter, causing the Bluetooth speaker to turn off by itself.

3.2 The role of BJT as an amplifier

Bipolar transistors are electronic components commonly used in electronic circuits. In an analog circuit, this transistor is used as an audio signal amplifier (amplifier) Smith, K. C. (2015). The role of BJT in audio systems lies in its amplifier circuit configuration which can affect the amount of gain, sound quality, and power efficiency. The use of configurations like common emitter has proven to produce significant signal amplification in portable devices (Kumar & Sharma, 2020).

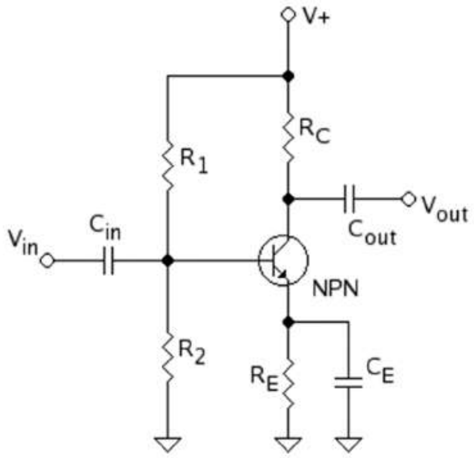

Figure 4. The role of BJT as an audio signal amplifier

Source: Adapted from Tgau, M. T., & Huong, N. T. M (2024).

Based on the image, the role of the BJT in the audio amplifier section is to amplify the incoming audio signal. This circuit employs a common emitter configuration using an NPN transistor due to its better design for amplifying audio signals, especially in Bluetooth speakers. When the audio signal enters the base of the transistor through the capacitor (Cin), this capacitor will pass the audio vibrations (AC). Resistors R1 and R2 serve to provide bias voltage to the base, which causes a small change in base current, resulting in a large change in collector current. When the audio signal starts to enter, the BJT will regulate a larger current from the collector to the emitter, thus strengthening the weak audio signal that has just entered the collector. The collector current flows through the resistor (RC), which will produce the output voltage (the amplified signal). The output Cout capacitor will regulate and separate the AC signal from the DC so that the audio signal can reach the speaker receiver with clear and crisp sound, and the resistor (RE) functions here to keep the performance of the BJT stable.

4. ADVANTAGES AND DISADVANTAGES

4.1 Advantages of Using BJT

The use of bipolar transistors (BJTs) as active elements in audio signal amplifiers in Bluetooth speakers offers several advantages, especially in terms of current gain characteristics and analog performance. One of the most striking advantages is its ability to operate efficiently at low to mid frequencies, with high current gain and low output impedance. These characteristics are very suitable for driving loads such as speakers, without the need for complex additional buffers.

Research by (Amewornu, E. M., 2015) shows that the design of audio amplifiers in wireless Bluetooth speakers is highly dependent on the selection of the right transistors, where BJTs provide the ability to control current well, ensure high sound quality, and minimize distortion. In his research, Amewornu emphasized the importance of optimal signal amplification for portable audio systems with high power efficiency. The selection of the right components, such as BJTs, improves power consumption efficiency and audio quality in wireless Bluetooth speaker systems. Furthermore, (Costa, 2018) in his research emphasized that the common-collector (emitter follower) configuration in BJTs provides superior linearity characteristics compared to other configurations. This configuration produces a more stable frequency response and minimal harmonic distortion, which is crucial for maintaining sound quality, especially in devices that prioritize audio reproduction accuracy. Through Early modeling, Costa also provides a quantitative approach that allows performance prediction based on the physical parameters of the transistor, thus facilitating circuit design optimization.

4.2 Disadvantages of Using BJT

Behind the advantages in terms of signal amplification, the use of bipolar transistors (BJT) also has several technical drawbacks that need to be considered, especially in audio amplifier applications such as Bluetooth speakers. One of the main problems is the sensitivity of BJTs to temperature changes and thermal instability. Increased temperatures during operation can affect the transistor's operating point, reduce amplifier performance, and under certain conditions can cause significant signal distortion or even permanent damage due to a phenomenon known as thermal runaway. Research by (Hasan et al., 2024) proves that the working parameters of BJT transistors are greatly influenced by temperature. In their study, the NPN type transistor 2SC2120 was tested at temperatures from 25°C to 130°C, and the results showed a significant increase in collector current and current gain as the temperature increased. The threshold voltage of the transistor also decreased from 0.6 volts to 0.4 volts, which means that the transistor becomes easier to conduct current as the temperature increases. However, if a Bluetooth speaker uses a bipolar transistor (BJT) as an audio signal amplifier, then prolonged use without an adequate cooling system can cause the temperature inside the device to increase significantly. As a result, the BJT becomes more sensitive to incoming signals and operates outside its optimal bias point, which leads to audio signal distortion, decreased sound quality, and disturbances in frequency response. In the long run, this condition can reduce power efficiency, accelerate thermal runaway, and even cause permanent damage to the transistor. All of this has a direct impact on the performance of Bluetooth speakers, such as sound that sounds broken, unclear, or even the device dies completely due to failure of active components.

Table 1. Collector current values based on temperature variations

		Collector Current (A)				
		25°C	75°C	95°C	115°C	130°C
Collector - Emitter Voltage V_{CE} (V)	1	0.13	0.40	0.61	0.82	0.21
	2	0.13	0.41	0.63	0.85	0.46
	4	0.14	0.42	0.66	0.91	0.71
	6	0.14	0.44	0.70	0.97	1.05
	8	0.15	0.50	0.76	1.02	1.15
	10	0.15	0.51	0.82	1.05	1.42

Source : Adapted From Hasan, G.T., Mutlaq, A. H., & Husain, M. H. (2024).

In addition, the capacitance value at the emitter-base junction increased dramatically from 10.1 nanofarads to 45.02 nanofarads at the highest temperature tested. These changes indicate that the transistor performance becomes unstable as the temperature increases, which is of course very risky in portable audio systems that often do not have adequate

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cooling systems. These findings make it clear that the use of BJT in systems such as Bluetooth speakers must be designed carefully, considering that thermal conditions can affect the gain characteristics and overall signal quality. When transistors operate in a confined space or at high currents without cooling, the potential for performance degradation is even greater. Although there are other approaches such as the use of transistors that offer better efficiency and linearity through harmonic suppression techniques, as noted by (Byeon and Kim, 2025), these approaches require more complex and expensive designs, which may not be suitable for simple and low-cost audio devices.

5. MANUFACTURING AND FABRICATION

Based on the process, the fabrication of BJT requires high precision doping and good thermal treatment in order to achieve BJT quality that provides good quality as a transistor, especially as an audio signal amplifier. BJT is composed of Germanium (Ge) and Silicon (Si) materials; however, from the shortcomings of these two semiconductor materials, there are also innovations in the creation of materials that make up the BJT. In this article, we review one of the bipolar transistor (BJT) fabrication processes as demonstrated in the GeOI study (Aggarwal et al., 2020). Ion implantation and RTA on GeOI—resulting in germanium layers with controlled strain (+0.4%) and low dislocation (2.7×10^{7} cm^{-2})—provides insights for the optimization of silicon BJT, particularly in terms of linearity and low noise.

5.1 Experimental details

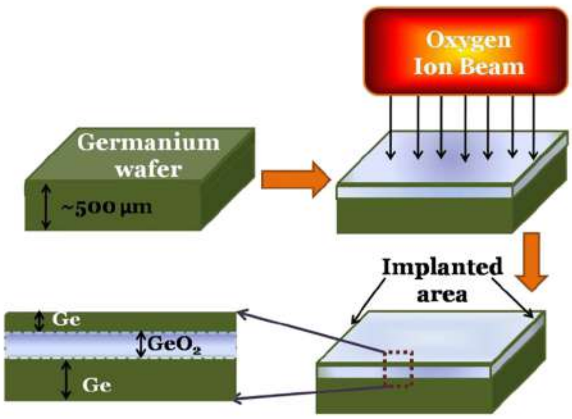

Figure 5. The process of making GeOI

Source : Adapted from Aggarwal et al., (2020)

In this process, a 100-oriented pure single crystal Germanium (Ge) wafer with a size of 1x1cm and a thickness of 0.5mm is used. This layer has a mobility of about 1130cm², a carrier concentration of 1.25×10^{14} cm^{-3}, and a resistivity of 44 Ohm-cm. The formation of the Germanium on Insulator (GeOI) structure is through oxygen ion implantation, where the layer is implanted with oxygen with an energy of 200V at a high dose of 1.9×10^{18} ions/cm² so as to form a GeO_2 layer in the Ge structure. After the implantation process, Rapid Thermal Annealing (RTA) was performed in a Nitrogen atmosphere to restore the damaged Ge structure. The annealing process was carried out at 650°C - higher than the GeO_2 glass transition temperature (≈580°C) - with two variations: rapid heating of 20°C/second for 3 minutes and slow heating of 5°C/minute for 1 hour. This temperature was chosen so that the initially amorphous GeO_2 layer turns into crystalline, while the Ge layer above it re-crystallizes, resulting in a good GeOI structure.

The Germanium-on-Insulator (GeOI) fabrication process is performed by implanting oxygen ions (O^+) into <100>-oriented pure Germanium wafers using 200 keV energy and a fluence of 1.9×10^{18} ions/cm² (Aggarwal et al., 2020). After implantation, the wafer was heated via Rapid Thermal Annealing (RTA) at 650°C in a nitrogen atmosphere to form an immersed oxide layer (GeO_2) and restore the crystallinity of the top layer of Germanium. As a result, a crystalline Ge layer about 220 nm thick is formed on top of a 620 nm thick crystalline GeO_2 layer, with a residual tensile stress of +0.4% and a dislocation density of about 2.7×10^7 cm-² (Aggarwal et al., 2020). This GeOI structure offers the advantages of high charge carrier mobility and good electrical insulation, which can improve the performance and efficiency of BJTs compared to silicon-based substrates (Marris-Morini et al., 2018). In addition, this method is simpler and more efficient than layer transfer or wafer bonding techniques, although the crystal quality is slightly lower (Lee et al., 2016).

6. CONCLUSION

The Bipolar Junction Transistor (BJT) plays an important role in audio signal amplification components (amplifiers) in Bluetooth speakers. The BJT functions to amplify weak input signals into stronger and clearer audio signals, making the sound output from the speaker clear. The BJT, which comes in NPN and PNP types, has characteristics that help regulate currents to be stable with a common emitter configuration, enabling the BJT to perform well in signal amplification. The BJT has advantageous features such as low output impedance and effective performance at low to mid frequencies, making it ideal for use as an audio signal amplifier in Bluetooth speakers. However, the BJT also has disadvantages, such as sensitivity to temperature, which can lead to a decline in sound quality and distortion due to high temperatures if there is no protective layer. However, BJT certainly also has disadvantages related to sensitivity to temperature, which can lead to a decrease in sound quality and the emergence of distortion due to high temperatures if there is no supporting layer such as cooling. In its fabrication, BJT requires innovation to continue to develop, where processes such as doping and thermal treatment like Germanium-on-Insulator (GeOI) fabrication can be used, resulting in improved performance and efficiency of the BJT components as amplifiers. Understanding the characteristics, working mechanisms, as well as the advantages and disadvantages of BJTs makes this component important in the development of modern audio systems.

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