Characterization of Ultrafast Superconducting Optoelectronic Devices

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Abstract:

Superconductors are materials that exhibit zero resistivity and ideal diamagnetism below a certain critical temperature, current and magnetic field. Zero resistivity is achieved by the formation of Cooper pairs (CP), which are paired electrons with opposite wave vectors and spins that are bonded together through electron-phonon interactions. In 1962, Brian D. Josephson theorized that CP's were capable of tunneling through an insulating barrier of a superconductor-insulator-superconductor (SIS) junction [2]. The phase coherence of these CP's produces unique electronic attributes of superconductive materials. Research in the field of low temperature superconductivity has focused on using Josephson junctions (JJ) for applications in digital electronics [5]. The JJ response that is produced when the junction switches into a resistive state is the single-flux quantum (SFQ). This is a voltage response that is equivalent to a logic "1" and could be used in superconducting digital circuitry.

Since the discovery of high temperature superconductors (HTS) in 1986 [1], much research and development has been carried out on these materials. Using Josephson junctions based on $YBa_2Cu_3O_{7-x}$ (YBCO) thin films, junction devices can generate ~1 picosecond wide pulses, corresponding to ~3 Terahetz operating speeds.

Many problems arise due to the physical limitations of terahetz operation of JJ's. Using JSPICE simulations and experiments, we characterized JJ properties for further understanding of the junction physics itself, as well as JJ applications in superconducting digital circuitry [7]. Experimentally, our ultrafast electronic circuits were measured using electro-optic sampling, which is sufficiently fast and sensitive to test the SFQ circuit performance.

With the possibility of using JJ's in digital circuitry, many parameters of the circuit require evaluation for further understanding. One motivation for simulation is testing the switching dynamics of grain-boundary JJ's that produce picosecond-wide single-flux quantum responses, which are applicable in digital circuitry. Simulations also investigate parameters of very fast optoelectronic circuitry to understand what input pulse requirements are necessary for the JJ operation.

As mentioned in the abstract, superconductors are materials that exhibit zero resistivity and ideal diamagnetism. Superconductive properties, however, are only maintained below a certain critical temperature, DC-current density and magnetic field, specific for various materials. Exceeding any of the critical parameters results in the loss of superconducting properties.

Both zero resistivity and ideal diamagnetism are a direct result of an attractive electron-electron interaction, mediated by phonons for conventional superconductors [1]. These interactions lead to the formation of pairs of electrons with opposite wave vectors and spins. These Cooper pairs are capable of tunneling across the potential barrier of a S-I-S junction. Figure 1 is a diagram of a simple JJ junction with the grain boundary cutting across the two superconducting plates [2]. The production of the grain boundary is quite simple. The S-I-S junction is made using a layer of YBCO material. It is configured by applying two substrate bases with different crystal lattice alignments and layering them with YBCO. Since there is a difference in alignment, the YBCO forms a border that has insulative properties, known as the grain boundary. Josephson predicted that below a certain critical current (I_C), there is no voltage drop across the junction, and the current is a harmonic function of the wave-function phase difference. Above the critical current, however, a voltage drop develops across the barrier, and there is a current oscillation with a frequency directly proportional to the voltage. Figure 2 is a representation of the voltage response that is generated when the critical current is exceeded.

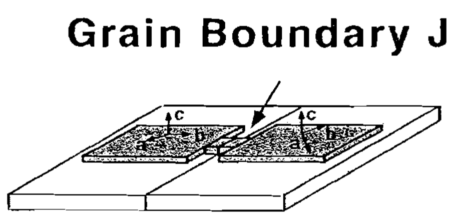

Figure 1: The single-flux quantum response is generated along the boundary as the current crosses the grain.

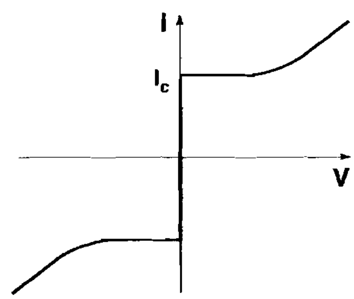

Figure 2: The occurrence of zero resistance is shown by the vertical line on the y-axis. The semi-curved line displays a current response when the junction "jumps" into a resistive state.

Currently, a relatively new and very unique approach of superconducting electronics is being pursued. It is based on overdamped JJ's [4]. Junctions with small capacitance are overdamped junctions that exhibit nonhysteretic I-V curves (see Fig. 2). These overdamped junctions use binary representation; however, logical states are represented not by two distinct voltage states, but by JJ-generated SFQ pulses with quantized area [1]:

$$V_{output} \approx 2 I_c R_n$$

$$\int V \cdot dt = \Phi_o \quad (\Phi_o \text{ is single-flux-quantum})$$

In SFQ circuits, junctions are biased just below their critical currents and a short control pulse (usually another SFQ pulse) drives the junction into a voltage state. In the voltage state, the junction produces an SFQ pulse with amplitude $\sim 2I_cR_n$ (where I_c is the critical current and R_n is the normal resistance of the junction) and pulse width $\sim \Phi_o/2I_cR_n$, and returns to the zero-voltage state. Since the junction remains in the voltage state for a very short period of time (single picosecond range), the power dissipated per pulse is extremely low and is in the order of $\Delta E \approx 10^{-18}$ J for junctions with I_c=0.5 mA [1].

An important parameter for SFQ circuit performance is the amount of time that it takes for the junction to respond to the applied bias transient, this is the turn-on delay time (T_D) of the JJ [7]. The T_D of a junction depends on various characteristics of the input pulse well as the junction damping and capacitance. Turn-on delay seems to be a larger factor when the junction damping and capacitance are high, and also when the transient amplitude is small.

The experimental setup and equivalent circuit used in JSPICE simulations are shown below in Figures 3a and 3b [1].

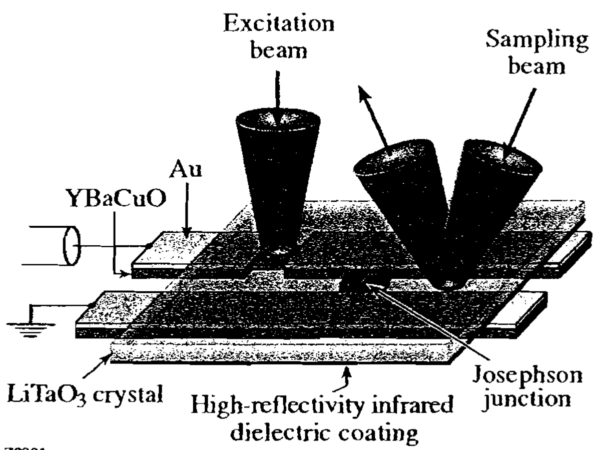

Figure 3a

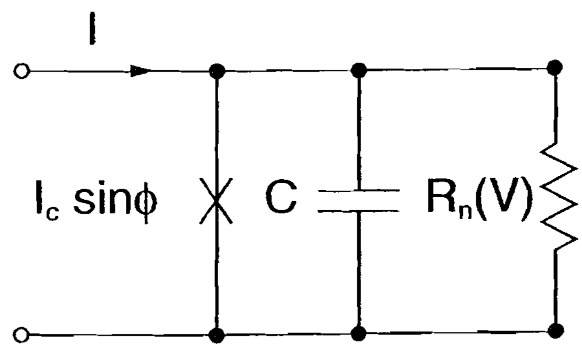

Figure 3b

In the experimental setup on the previous page, an excitation beam strikes the YBCO thin film where the gold layer was extracted. This excitation beam produces an electro-magnetic pulse that propagates along the transmission line (the gap between the two plates) towards the Josephson junction. When this pulse reaches the junction, the excess current causes the junction to switch into a resistive state. This resistive state produces a voltage response, the SFQ pulse, which could be used in digital circuitry [8]. The equivalent circuit (Figure 3b) is used for the numerical simulations of the circuit response. In the simulated circuit, the input pulse propagates from the left side of the diagram to the right. The Josephson junction is represented by an X. The junction capacitance and normal resistance is added to the simulation to duplicate as many of the experimental parameters as possible. Through these simulations various properties of the input pulse as well as the junction were examined.

The critical overdrive of the Josephson junction is an important attribute that if totally understood, benefits substantially to the ongoing research of the junction. The overdrive of a junction is the amount of current required to produce a resistive state in the junction. It is the minimum current that will produce a voltage response. Figure 4 shows the mechanics behind the overdrive of a junction. In Figure 4 the junction bias is represented by the red dot in the vertical range of the I-V curve [4]. The excitation beam (current pulse) must be larger than the point where the junction loses it's superconductive properties. The loss of superconductive properties implies that a voltage output is produced by the junction. The amount of current above the point where the junction is in a normal state is considered the overdrive.

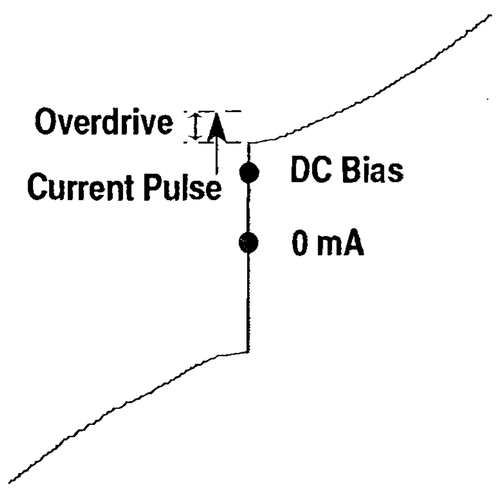

Figure 4

Variations in overdrive occur due to changes in critical current. Also, the bias current plays a significant role in junction overdrive. Using JSPICE, some unexpected results were produced that actually seem contrary to junction operation, but were substantiated by further testing with various critical currents.

As mentioned on the previous page, the unanticipated results occurred with changes in the required critical current of the junction. It was evident that a decrease in critical current required a larger overdrive when intuition would believe otherwise. According to simulations, a critical current of 0.5 mA required about four times as much current (compared to itself, meaning an overdrive of about 2 mA) compared to the 0.5 mA overdrive that the 2 mA critical current needed to produce a resistive state. Figure 5 is a graph that displays an increase in overdrive as a function of decreasing the critical current. In addition, according to the graph, an increase in the DC bias at every critical current requires a smaller quantity of pulse current or overdrive to produce a response. Looking at just one curve on the graph, a junction is expected to respond with any input pulse greater than the curve. All points below the curve produce no SFQ output. This is a major contribution to superconductive studies since minimum overdrive requirements were calculated for various critical currents.

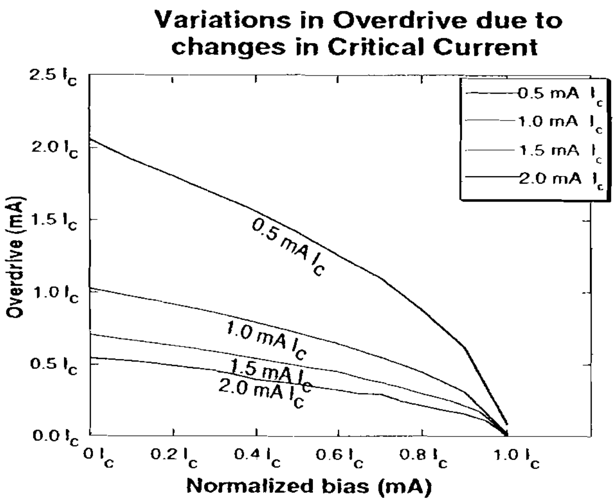

Figure 5

Pendulum Model

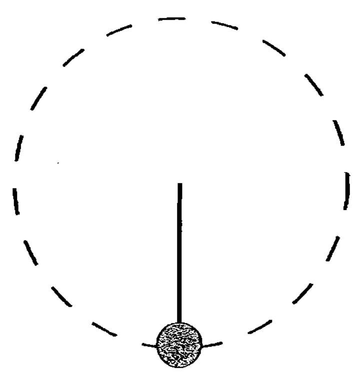
Figure 6

A simple model is used to describe the concept behind the overdrive of a JJ. The pendulum model (Figure 6) fully describes a response of JJ taking into consideration the overdrive parameter [9]. A complete revolution of the pendulum is equivalent to a voltage output produced by the junction. The DC bias is represented by starting the junction at a position other than the resting position.

A high DC bias is conceived by locating the pendulum closer to the top of the circle. The overdrive is the amount of power that is required to cause the pendulum to complete the full revolution. Hitting the pendulum really hard will push it over the peak and produce the SFQ output. The harder the hit, the faster and more certain a response will be produced. For example, if the pendulum is not hit hard enough, then it will not complete a full revolution, thus not producing the anticipated voltage response. It is also important to note that the pendulum will never fall below the point it is biased at.

Another important characteristic of the Josephson junction deals with the amount of time that it takes for the junction to respond to a transient pulse. Briefly mentioned before, this time delay between the pulse and the junction response is known as the turn-on delay of the JJ. There are two major factors of turn-on delay based on parameters of the input pulse. The pulse width and pulse amplitude cause similar results on junction output. Figures 7a and 7b display the similarity between outputs originating from varying pulse amplitudes and widths respectively, and also what is implied by varying pulse amplitude and pulse width.

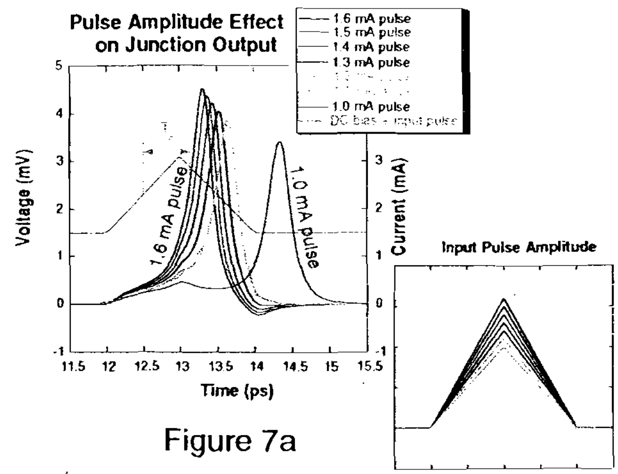

Figure 7a

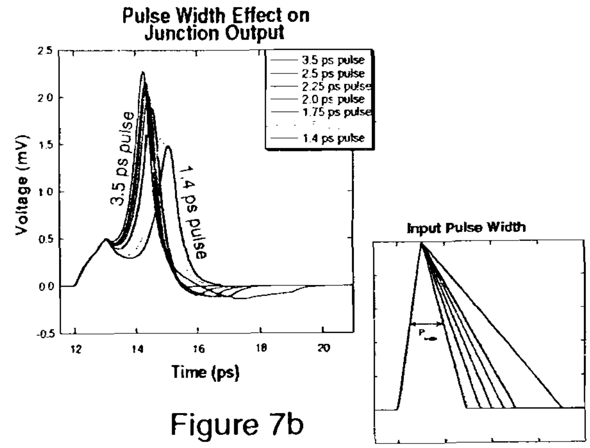

Figure 7b

In Figure 7a, the gray line that forms a pyramid represents a transient pulse. The other line with the arrowheads and the label T_d symbolizes the points at which turn-on delays are calculated. Turn-on delays are measured from the point at which 50 percent of the input pulse strikes the junction to approximately 65% of the junction response. It is measured in picoseconds. Usually the turn-on delay does not surpass 4 to 5 picoseconds.

Both graphs show similar trends. When either the pulse amplitude or pulse width are increased, the turn-on delay decreases. This means that the junction is responding at a faster rate than the previous simulation. Another observation was that the amplitude of the output decreased with an increase in turn-on delay. This decrease in pulse amplitude is justifiable. From the given equation on page three, the single-flux quantum voltage response is the integral of the voltage as a function of time. This SFQ response must remain constant by the equation of $V_{output} \approx 2I_cR_n$. From these two equations, it is deduced that as the turn-on delay increases from variations in pulse amplitude or pulse width, the area below the voltage curve is kept constant by a decrease of the SFQ amplitude. Smaller pulse amplitudes or widths cause junction interference, which is the area of the voltage curve before the actual response is produced. These pulses do not have the required overdrive immediately, but eventually do cause the junction to respond, thus producing longer turn-on delays. Once the basic parameters of pulse width and amplitude were tested, experimentation was necessary to produce a critical input pulse width and amplitude.

A critical input pulse width is a required width that causes the junction to respond with an SFQ output with any width exceeding the measured quantity. The input pulse width is measured at fifty percent of the pulse amplitude. Two different critical currents were examined each with variations in the overdrive. In retrospect, the overdrive is the amount of current above the critical current that are necessary to cause a junction response. Figures 8a and 8b display results on the critical input pulse width for 1 mA and 2 mA critical currents.

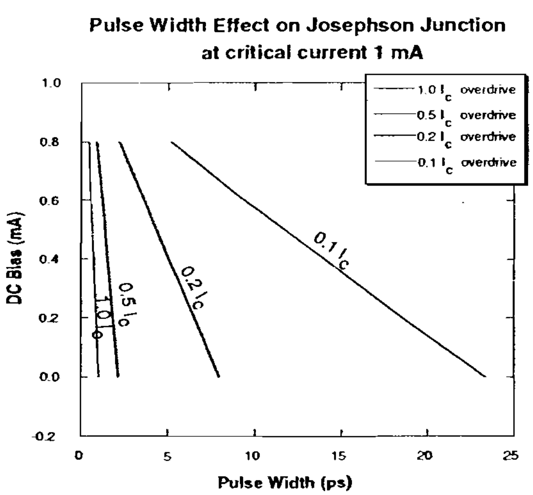

Figure 8a

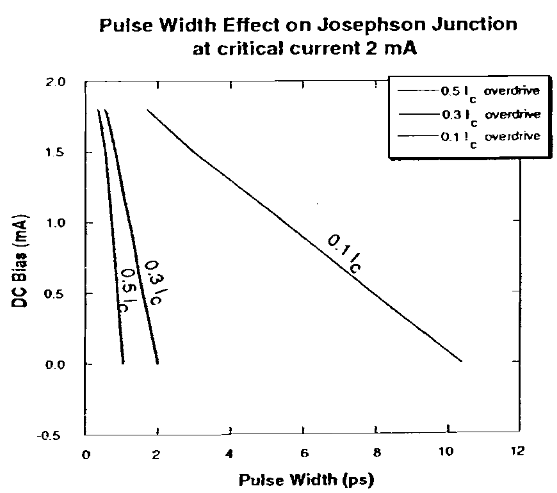

Figure 8b

From the results on the previous page, many deductions can be made. It is obvious that an increasing overdrive produces faster outputs from the junction. This is proven by the steeper sloped curves on both graphs. More importantly, an increasing overdrive requires a smaller pulse width, measured in picoseconds, to produce the SFQ pulse. Using this piece of information in the lab, high overdrives require smaller pulse widths, and therefore are capable of faster junction responses. Observations on DC bias reveal that a narrow pulse width is needed with increases in the bias. This too improves the frequency of outputs that are produced by the JJ. On both the 1 mA and 2 mA graphs, any pulse width that is greater than the lines labeled as various overdrives will cause the junction to respond. For example, looking at the 0.1 I_C overdrive on the 1 mA critical current, a 14 picosecond pulse will induce an SFQ at a DC bias of 0.4 mA. At the same DC bias, the JJ will respond with a 17 picosecond pulse width, but not a 10 picosecond width.

Understanding this data is crucial in formulating relevant experiments in the laboratory. For instance, knowing the pulse width that will produce SFQ's at various DC biases simplifies experimentation. It is then possible to calculate a range of optimal input pulse widths, where neither output or input pulse frequencies are hindered. If for instance, a 20 picosecond input pulse width is required for junction response, there is a 20 picosecond delay time before another pulse is processed by the JJ for usage in digital circuitry. Reducing that width to about a fourth would quadruple JJ response to excitation pulses. It is also important to note again that higher overdrives reduce pulse widths necessary for wanted results. With these factors in mind, experimentation in the lab is benefited by outcomes produced in JSPICE simulations.

Comprehending input pulse width is just the beginning. On page six it was noted that there was a similar effect on junction output with variations in input pulse width and amplitude. Therefore, there must be a dependency between input pulse amplitude and width Using JSPICE simulations, the parameters of requirements on the input pulse were fully examined. The data collected also has much relevance to the laboratory. In general, an increase in input pulse amplitude causes a reduction in the input pulse width required to produce an SFQ response by the junction and vice-versa. Using this data and the data from the critical pulse width, an overall picture is drawn on some specified requirements to produce optimal JJ output. A range of amplitudes and widths capable of producing favorable outcomes has to be considered in experimentation. If either the input pulse amplitude or width are to large, multiple SFQ outputs are produced. Looking back on the pendulum mode on page five, hitting the pendulum too hard could cause it to revolve numerous times, which is equivalent to more than one output. This is an unfavorable outcome and therefore must be eliminated. Reducing the pulse width at a critical point requires a larger pulse amplitude for the JJ to respond.

In this fashion, reducing pulse width, which reduces delay-time for the junction to respond to following inputs, increases the required amount of input amplitude, and controlling output. Figure 9 shows the dependency of input pulse amplitude and width in greater detail. The graph compares pulse amplitude and pulse width for various DC biases for a 1 mA critical current. It is evident from the chart that an increase in pulse width reduces the necessary pulse amplitude required to produce an SFQ. With this data, experimentation adjusts for variations in either the amplitude or the width of the incoming input pulse. Closely related to pulse width, the rise time of the input pulse causes an impact on junction response.

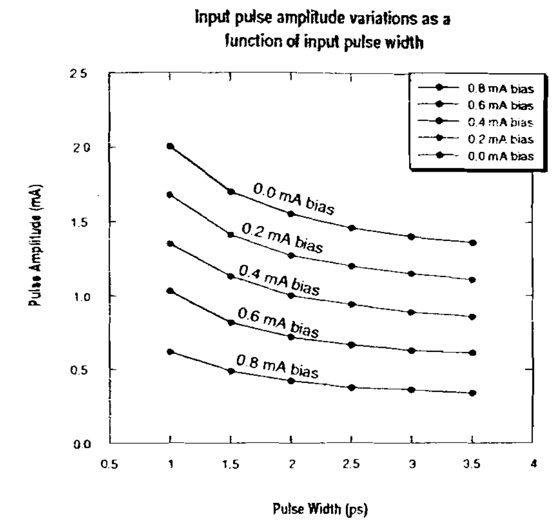

Figure 9

The rise time of an input pulse is the amount of time, in picoseconds, measured from about twenty percent of full amplitude to eighty percent of full amplitude. Variations in rise time usually display changes in delay-time and reduce the required input pulse amplitude or width. In JSPICE simulations, a 1 mA critical current was tested with variations in DC bias at three different overdrives: a 0.1 I_C, 0.2 I_C, and a 0.5 I_C overdrive. Figures 10a, 10b, and 10c display outcomes with these variations in the input pulse risetime.

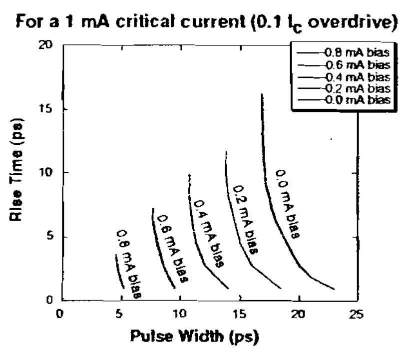

Figure 10a

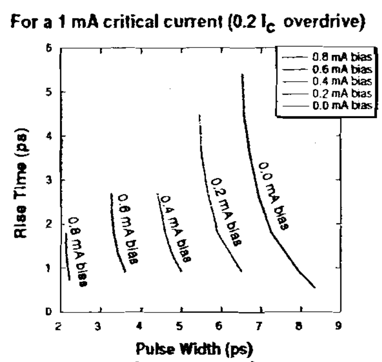

Figure 10b

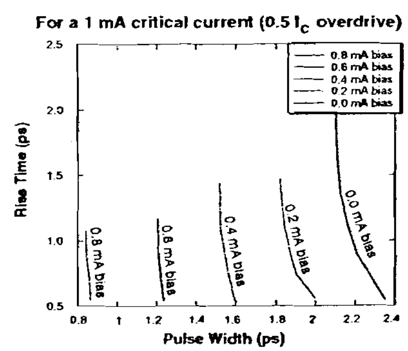

Figure 10c

From the data, it is evident that a general decrease occurs in pulse width as the rise time of the input pulse increases. This too is beneficial, especially when observing wider input pulses. With large input pulses, increasing the rise time of the input pulse will actually reduce the pulse width, thus making the junction more efficient in processing proceeding input pulses. In addition, looking at individual graphs, a higher DC bias reduces either the pulse width or rise time requirements. Therefore, changes in the bias are crucial for optimal junction response, as mentioned before. It is also important to note that at each DC bias, a response occurs to the right of the curve, while no SFQ is produced on the left side.

In conclusion, all characteristics of the input pulse are crucial for the Josephson junction to respond as predicted. A change in one variable produces variations in the expected results. Through JSPICE simulations, variations in input pulse parameters were experimented with, and it was evident that their correlation is very intertwined. This means that changing one parameter produces a change in other parameters, and if used correctly could be very beneficial to experiments performed in the lab. Further understanding of these properties is extremely beneficial to further comprehending the junction physics and to possibly develop superconducting digital circuitry using JJ as a means of producing voltage responses equivalent to logic 1 in contemporary circuitry.

Acknowledgements

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