Quantum Computing with Bismuth Compound Bi-2212 Josephson Junction at 0.5 Kelvin

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***Abstract*—The research goal is to construct a quantum computer. In the lab, a quantum computer prototype has been built with a superconducting compound of Bismuth (BS 2212), which is layers of compounds designed to work as a solid type quantum computing device at temperature of 0.5 Kelvin or lower. The target operating temperature of the quantum computer will be 0.02 Kelvin using a mixture of helium 3 and helium 4. At the mean time, the measurement and testing of the quantum computer prototype is taking place.**

I. Introduction

In 2001, IBM announced a liquid state quantum computer which uses 7 qubits to perform Shor's algorithm. [3] Shor's algorithm is an algorithm for factorization. The IBM research described the Shor's algorithm in the quantum computer was able to factor large numbers exponentially faster than conventional computers. The algorithm is fast enough to defeat the security of many public-key cryptosystems. In other words, if the quantum computer is fully developed, the computer will be able to crack any secret code or any secret password in any computer. The IBM quantum computer is shown in Fig. 1.

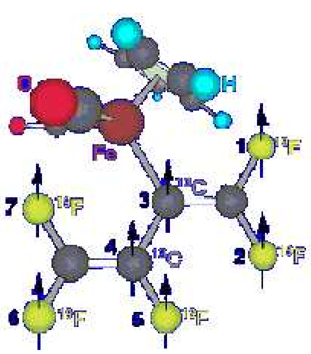

Fig. 1. IBM Quantum Computer using 7 qubits announced in 2001.[3]

Unfortunately, the quantum computer described by IBM was a liquid based quantum computer which requires a very low temperature and is hard to be commercialized. In this case, high temperature superconductor is considered more possible to be commercialized.

II. Types of Quantum Computer

Type of Quantum Computer	Number of Qubit
Charge (NEC, 1999)	1 qubit
Phase (NIST, 2002)	1 qubit
Charge (Chalmers, 2002)	1 qubit
Phase/Flux (Delft, 2002)	1 qubit
Charge (NEC/Riken, 2002)	2 qubit
Charge (NEC/Riken, 2002)	2 qubit
Charge (NEC/Riken, 2002)	2 qubit

There are three types of solid state quantum computers. Quantum computers base on either a phase qubit, a flux qubit, or a charge qubit. The type of quantum computer being constructed in this Research Institute of Electrical Communication (RIEC) laboratory is a phase qubit quantum computer.

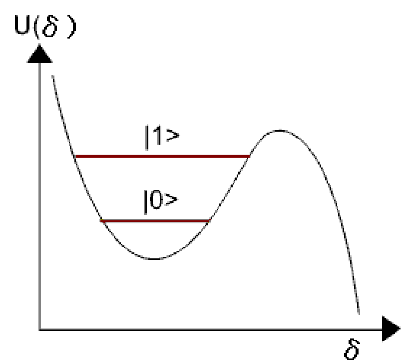

Fig. 2. The design of the phrase qubit quantum computer have two distinct energy levels, energy level 0 and energy level 1. When electromagnetic wave of a particular frequency is absorbed by electrons in energy level 0, the electron at energy level 0 will jump up to energy level 1. The electron at energy level 1 can also emit electromagnetic waves and go back to energy level 0. As the electron changes its energy level, calculation can be done and information can be store.The vertical axis in the graph is the potential energy with respect to the phase, and the horizontal axis is the phase.

The design of the phrase qubit quantum computer is shown in Fig. 2. The vertical axis in Fig. 2 is the potential energy with respect to the phase, and the horizontal axis is the phase. The quantum computer has two distinct energy levels, energy level 0 and energy level 1. When electromagnetic wave of a particular frequency is absorbed by electrons at energy level 0, the electrons at energy level 0 will jump up to energy level 1. The electrons at energy level 1 can also emit electromagnetic waves and go back to energy level 0. As the electron changes its energy level, calculation can be done and information can be store. At this moment, the part responsible for generating the necessary electromagnetic wave to excite the electron in energy level 0 is not yet implemented. The equipment responsible for generating such electromagnetic wave is ready to be used, but the actual implementation will be after the verification of the physical parameters of the Bi-2212 superconductor Josephson Junction.

III. The Physical Setup of Lab Equipments

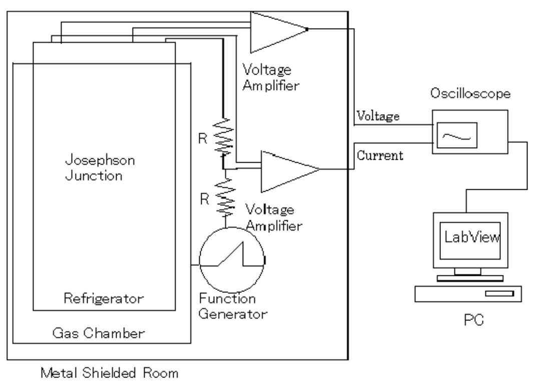

Fig. 3. The experimental setup of Josephson Junction in a nitrogen-helium refrigerator at 0.5 Kelvin.

In Fig. 3, the schematic of the Research Institute of Electrical Communication (RIEC) laboratory setup is shown. The Josephson Junction, which is two superconductor with an insulator in between, is essential for quantum computation. The Josephson Junction is placed in a nitrogen-helium refrigerator. Liquid nitrogen and liquid helium are constantly circulating around the Josephson Junction to keep the sample in low temperature. The temperature is kept low enough for quantum effects to occur.

The nitrogen-helium refrigerator is consisted of different layers of gas. First of all, at the outermost layer is the vacuum layer. At room temperature 300 Kelvin, the heat is blocked off from the nitrogen-helium refrigerator mainly at the outermost vacuum layer. Inside the vacuum layer, it is a layer of liquid nitrogen. The liquid nitrogen is at temperature 77 Kelvin. If the temperature reaches 77 Kelvin, the liquid nitrogen evaporates. The pressure of the nitrogen gas is kept at atmospheric pressure. In fact, the nitrogen gas is constantly being let out of the gas chamber to keep the pressure inside of the gas chamber to be constant. If you see the gas chamber, you will see a rubber tube with white and cold nitrogen gas blowing out of the gas chamber. The rubber tube that let out the nitrogen gas is usually coated with a layer of ice. As the ice on the rubber tube becomes thicker and thicker, the ice may block the flow of nitrogen gas. There was an incident when the rubber tube was blocked and pressure was built up inside the gas chamber, a safety valve was broken off. In other words, the nitrogen gas caused a small explosion inside the gas chamber. As a safety measure, if pressure is built up inside the gas chamber to a dangerous level, the safety valves will let out some of the helium gas or nitrogen gas. If pressure is being built up and there are no safety valves, the pressure in the tank will eventually cause the whole gas chamber to explode.

Inside the vacuum layer and the nitrogen layer, liquid helium 4 is being circulated. The liquid helium 4 brings down the temperature to 4.2 Kelvin. The helium gas is recycled and is not released to the open air. Helium gas is more expensive than nitrogen gas, so helium cannot be released to the open air. Inside the liquid helium 4 layer, there is the coldest part of the nitrogen-helium refrigerator. There is a mixture of helium 3 and helium 4, and the temperature is at 0.5 Kelvin or lower. The lowest temperature reached in the innermost layer is 0.04 Kelvin.

The liquid helium and liquid nitrogen in the nitrogen-helium refrigerator need to be exchanged 2 times per week. 100 liters of liquid nitrogen and 100 liters of liquid helium are exchanged per week. The helium gas is transferred to another facility outside of the laboratory for recycling, and the old nitrogen gas is released to the air. New liquid nitrogen is transferred into the gas chamber during the gas exchange.

Magnetic field was used to lower the critical current I_c of the Josephson Junction. There is theory about how the critical current I_c of the Josephson Junction would behave according to the magnetic field. A magnetic field generator is connected to the electromagnet placed inside the nitrogen-helium refrigerator. A maximum value of 7 Tesla was reached, but the strength of the magnetic field was not strong enough to produce a desired critical current value.

IV. The Structure of the Josephson Junctions

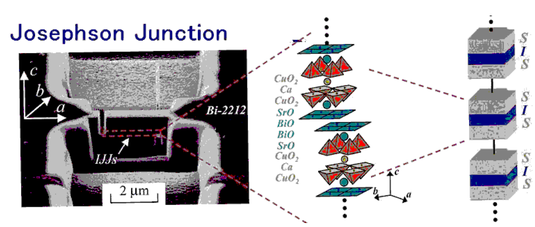

Fig. 4. The physical construction of Josephson Junction in the nitrogen-helium gas refrigerator. A Josephson Junction is created by layers of Bismuth compounds(BiO), Strontium Oxide (SrO), Copper Oxide (CuO_2), and Calcium (Ca). The chemical formula of the compound is $Bi_2Sr_2CaCu_2O_{8+x}$ or Bi-2212 for short.

In this Research Institute of Electrical Communication (RIEC) laboratory, a Josephson Junction is created by layers of Bismuth compounds(BiO), Strontium Oxide (SrO), Copper Oxide (CuO_2), and Calcium (Ca). The chemical formula of the compound is $Bi_2Sr_2CaCu_2O_{8+x}$ or Bi-2212 for short. See Fig. 4. A Josephson Junction is two superconductors with a layer of insulator in between. In the case of the experimental construction of the Josephson Junction in the laboratory, the CuO_2-Ca-CuO_2 layer at the top and at the bottom are the superconductor layers, the middle SrO-BiO layer is the insulator layer.

The original design was to use one single Josephson Junction with the size of 3 Å (3 Angstrom) for the superconductor portion, and 12 Å for the insulator portion. Due to manufacturing difficulties, the Josephson Junction was made with 20 Josephson Junctions connected in series. Since the construction of the series of Josephson Junctions is different from the ideal construction using only one single Josephson Junction, the physical properties of the setup has to be verified. In other words, all the equations and laws published by various papers may work for a single Josephson Junction. However, those equations may not work with 20 Josephson Junctions in series.

V. Kramer's Equations

$$\omega_{J0} = \sqrt{\frac{2\pi I_c}{\phi_0 C}} \quad (1)$$

$$\omega_J = \omega_{J0}(1-\alpha^2)^{\frac{1}{4}} \quad (2)$$

$$\alpha = \frac{I}{I_c} \quad (3)$$

$$U_0 = E_J[-\pi\alpha + 2\{\alpha \sin^{-1}\alpha + (1-\alpha^2)^{\frac{1}{2}}\}] \quad (4)$$

$$E_J = \frac{\hbar I_c}{2e} \quad (5)$$

$$\tau_{TA}^{-1} = \frac{\omega_J}{2\pi} e^{(\frac{-U_0}{k_B T})} \quad (6)$$

$$\tau_{MQT}^{-1} = 12\omega_J \sqrt{\frac{3U_0}{2\pi\hbar\omega_J}} e^{\frac{36U_0}{5\hbar\omega_J}} \quad (7)$$

$$P_\alpha = (\frac{d\alpha}{dt})^{-1}\tau^{-1} e^{-\int_0^\alpha \tau^{-1}(\frac{d\alpha'}{dt})^{-1} d\alpha'} \quad (8)$$

Here ω_J is the plasma frequency in radian per second, I_c is the Josephson critical current, e is the charge of electron 1.6×10^{-19} joule·second, k_B is the Boltzmann's constant $1.38 \times 10^{-23} \frac{Joule}{Kelvin}$, h is the Plank's constant 6.63×10^{-34} coulomb, ϕ_0 is the basic flux unit 2×10^{-7} gauss·cm, and P_α is the probability of either thermal activation or macroscopic quantum tunneling (MQT).

With the equations 1 through 8, one is able to calculate the probability of having an electron crossing over the potential barrier. Quantum computing will be able to be performed when there is no crossing over. In other words, the quantum computation must be performed before an electron cross over the potential barrier. The quantum data must be collected before an electron cross over the potential barrier or the quantum data will be disturbed by the crossing over of the electron.

VI. The Probabilities of Critical Current

According to Voss and Webb through their publication in 1981, the probabilities of the critical current is shown in Fig. 5. The critical current is the I_{SW} on the horizontal axis of the Fig.. In Fig. 5, I_{SW} stands for switching current, which is the same thing as critical current I_c of the Josephson Junction.

The Fig. shows the distribution of the critical current I_c of the Josephson Junction at temperature below 2 Kelvin. The critical current I_c of the Josephson Junction decreases as the temperature increases. When temperature is below 1 Kelvin the probability has sharp peeks, and the value of the probability is high. In other words, the critical current at temperature lower than 1 Kevin is relatively more definite, and the range of critical current is within a narrow range.

When the temperature reaches 1 Kelvin or above, the probability is more spread out, and the value of the probability is generally lower. In other words, the probability of finding the critical current is less certain at temperatures higher than 1 Kelvin than at temperatures lower than 1 Kelvin. The reason is when temperature is high, there are thermal effects acting on the experimental setup as a source of error. The true value of the critical current is disturbed as temperature rises.

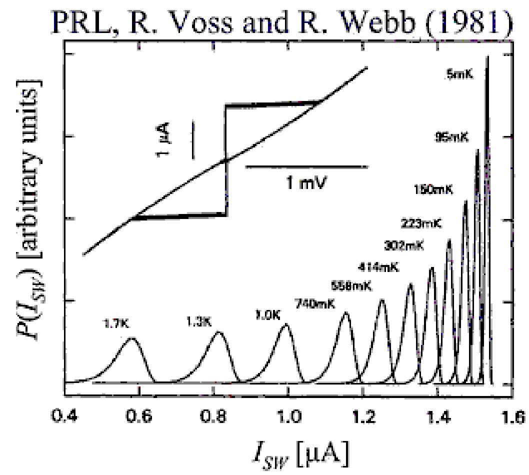

Fig. 5. The probability distribution of switching current at different temperatures according to Voss and Webb.

The experimental values obtained in the Research Institute of Electrical Communication (RIEC) laboratory can be compared against the values published by Voss and Webb. If the values agree with each other, that will be a good indication the experimental setup is accurate and the temperature control is efficient. At the mean time, testing of the experimental setup against the values published by Voss and Webb is taking place. In other words, the quantum computer design within the low temperature gas chamber is being tested for the measurability of quantum effects. In simple words, we are trying to see if the setup is giving us what the setup should give us.

VII. The Measurement of Experimental Setup

The measurement of the values produced by the quantum computer is one of the biggest challenges. Since every time a measurement is taken, the value is disrupted by whatever is taking the measurement. There are error correction techniques developed by Chuang in IBM. Most probably the error correction technique will be applied to the quantum computer in the Research Institute of Electrical Communication (RIEC) laboratory later on. Taking measurement of values produced by quantum computer is somewhat a final step of the research. At the present stage, the value of the quantum computer can not yet be accurately measured due to the uncertainty of the physical conditions of the Josephson Junction.

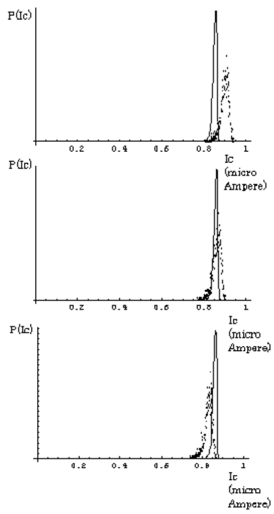

Fig. 6. Plots generated by Mathematica are used to find the critical current I_c. The solid line is the theoretical value and the dots are experimental data. In these plots, the closest fitting is the plot in the middle. By keep guessing the value of I_c in a more and more narrow range and keep doing KLI error fitting, the value of critical current I_c can be determined. In Kramer's Equations, critical current I_c is the only value needs to be determined experimentally. See equations in page 3.

When the value is being measured, the potential hill shown in Fig. 2 on page 1 will be lowered. The electron at energy level 1 will be able to escape the potential well by thermal activation. In other words, if the energy level 1 gives you enough electrons of a particular energy, the value measured is 1. Similarly, if the energy level 1 does not give you enough electrons of a particular energy, the value measured is 0. The energy of the escaped electron can be measured and compared against the target probability obtained from equations given by Kramer's equations, see page 3 for the equations. Since the actual value obtained has to be determined by a distribution of probability, which means multiple runs have to be performed to determine a single value. In order to perform multiple runs to get the same value, measurements are made after a regular interval of time. In other words, when the experimental setup is ready, you turn on everything and wait. You wait a while, say 5 mini-seconds, and take one measurement. The measurement obtained is the critical current value in ampere, and then you repeat every 5 mini-seconds until you take the value 2000 times. What you ultimately get is a distribution of probability.

In terms of the measurements that are being obtained at this moment, the values are used to determine important parameters like the critical current I_c of the Josephson Junction. The critical current I_c of the Josephson Junction is the only parameter that depends on the experimental setup in the equations shown in page 3. In other words, if the exact value of the critical current I_c of the Josephson Junction is known, then everything the equations in page 3 can be calculated. I was able to measure the experimental setup and get the first-hand experimental data. I used the LabView program and get the distribution of probability. I stored the data into a text file and imported the data into Mathematica. Despite the difficulties learning Mathematica, I generated plots to find the critical current I_c. The solid line in Fig. 6 is the theoretical value and the dots are experimental data. In the plots shown in Fig. 6, the closest fitting is the plot in the middle. I took the value of critical current I_c, and ploted the graphs with one more digit after the decimal. By keep guessing the value of I_c in a more and more narrow range and keep doing KLI error fitting, the value of critical current I_c become more precise and a final value critical current I_c can be determined. The value of critical current I_c I found is 2.5385 micro Ampere(μA, or 2.5385×10^{-3}). From the critical current I_c, the plasma frequency ω_J calculated is 3.18×10^{11} rad/sec. The critical temperature T calculated, which is the T* in Fig. 8 on page 5, is 0.68 Kelvin.

VIII. The Difficulties of Quantum Computing

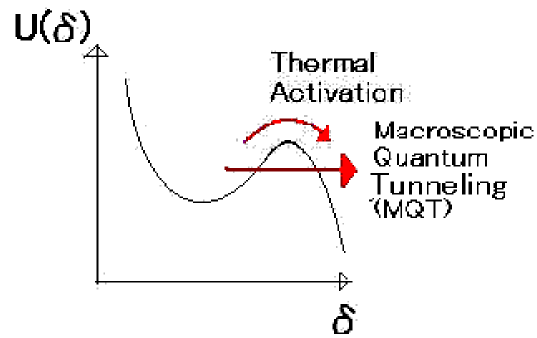

Fig. 7. The vertical axis is the potential energy with respect to the phase, and the horizontal axis is the phase. The electron that is trapped in the potential well always want to escape from the potential well either by thermal activation or by Macroscopic Quantum Tunneling (MQT).

The value store in the potential well of the quantum computer, see Fig. 2 on page 1, is very unstable. The value is affected by temperature and quantum tunneling. The effect due to temperature called thermal activation is the classical model of electron in the potential well trying to escape the potential well. The electron would climb up the potential hill and then go down the potential hill to the other side. On the other side of the potential hill, the value can be measured.

The electron in the potential well can escape the potential well to the other side of the potential hill, see Fig. 7, by quantum tunneling or Macroscopic Quantum Tunneling (MQT). The electron that is trapped in the potential well will tunnel through the potential hill without gaining potential energy. This is a quantum effect.

During the calculation, both thermal activation and Macroscopic Quantum Tunneling (MQT) are not desirable. Thermal activation can basically be eliminated by lower the temperature. The Macroscopic Quantum Tunneling (MQT) on the other hand is not likely to be completely eliminated. In this case, the rate of Macroscopic Quantum Tunneling (MQT) is calculated, and quantum computation has to be performed before Macroscopic Quantum Tunneling (MQT) occurs. The period of time allowed for computation is called the decoherence time. The decoherence time generally means the time before the quantum value is disturbed.

The behavior of thermal activation and Macroscopic Quantum Tunneling (MQT) can be study in Fig. 8. When the temperature is above the critical temperature T, both thermal activation and Macroscopic Quantum Tunneling (MQT) are taking place. When the temperature is sufficiently high, thermal activation is the main effect taking place and Macroscopic Quantum Tunneling (MQT) is quite negligible. When the temperature goes below the critical temperature, thermal activation is basically cut off, and Macroscopic Quantum Tunneling (MQT) is the only meaningful effect. The rate of MQT stays relatively constant below the critical temperature.

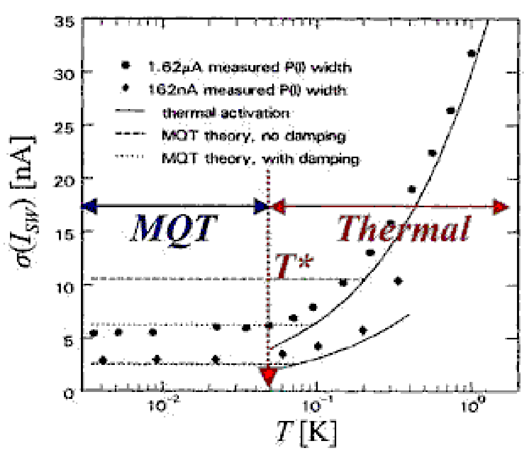

Fig. 8. When temperature is above the critical temperature, thermal activation is the dominant effect responsible for the transition of electron across the potential hill. When temperature is lowered further and further, Macroscopic Quantum Tunneling (MQT) should be the dominant or only effect responsible for the transition of electron across the potential hill.

IX. The Controlling Unit and Data Collection Unit

Both the controlling unit and the data collection unit of the quantum computer are designed in LabView programs. The controlling unit consists of a computer, a gas controller, and 2 pumps. The controlling computer is connected to the gas controller, which is a large metal box regulating the speed of the inflow and outflow of the gas. The nitrogen gas and helium gas are being circulated between the nitrogen-helium refrigerator in the metal room and the pumps outside the metal room. The pumps keep the gases circulating during normal situations.

A subset of the control panel is shown in Fig. 9. The pressure and temperature are constantly monitored by the controlling unit. If the temperature in the nitrogen-helium refrigerator is too high, measurements cannot be done. At such time when temperature is too high, everyone has to wait for the Josephson Junction to cool down before taking another measure.

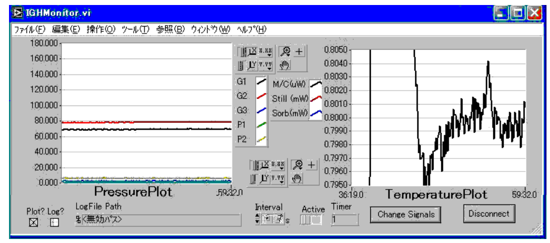

Fig. 9. A LabView program is used to monitor and control the gas pressure and the temperature inside the nitrogen-helium refrigerator. Temperature is kept at around 0.5 Kelvin during operation.

Two amplifiers take the signals produced by the Josephson Junction and amplify the signal. The amplified signals are carried out of the metal room, and are collected by a digital oscilloscope. The data are displayed in the digital oscilloscope and are also transmitted to a computer. The data collecting computer has a LabView Program to store the data in the computer for further investigation. Part of the panel is shown in Fig. 10. The Fig. shown in Fig. 10 is the probability distribution of the critical current I_c. Raw data are collected from 2000 sample values in every run. A run takes around 20 minutes to take the 2000 samples.

When the effect of magnetic field is being investigated, the magnetic field will have to change from, say 1 Tesla to 2 Tesla, then it will take 20 minutes to find the critical current I_c. After that, the Josephson Junction needs to be cool down for another 20 minutes or so. After the sample is cooled down, the magnetic field will be change again, say from 2 Tesla to 3 Tesla, then we measure the critical current I_c again. So the procedure repeats again in this pattern until the physical parameters of the quantum computer are known for sure.

At the mean time, since the temperature of the nitrogen-helium gas refrigerator reaches 0.5 Kelvin, testing has been done in the laboratory to find out whether Macroscopic Quantum Transition (MQT) is the only effect taking place. By theory, crossing over the potential barrier through classical thermal excitation should be blocked at such low temperature, and MQT should be the only effect taking place.

X. Quantum Computer versus Semiconductor Computer

Since several decades ago, the semiconductor industry was able to create faster and smaller computer every year, however, in 20 years this will no longer be true. By that time, the scale of transistor, which is a basic computation unit, will approach the size of an atom. More importantly, the heat dissipation may approach the temperature of the Sun if semiconductor technology continues to grow at the speed stated by Moore's Law. In other words, semiconductor technology is expected

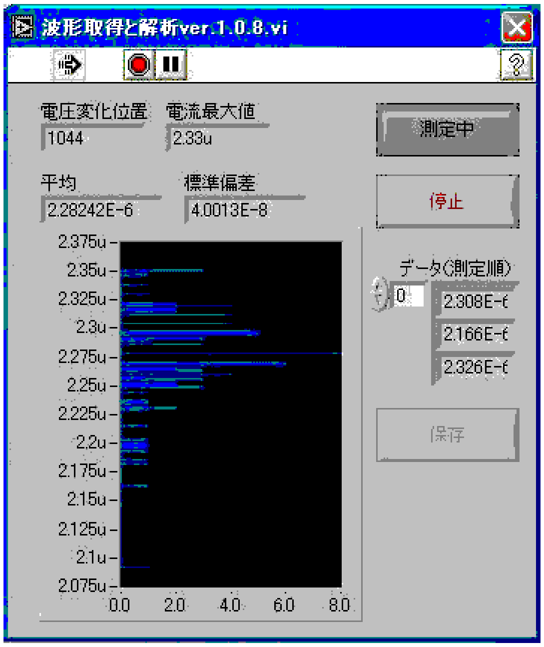

Fig. 10. The electrical signal from the amplifiers are collected by a digital oscilloscope and the data are monitored and stored by a LabView Program.

to saturate and stops growing, and at that time quantum computing era begins.

Quantum computer is expected to exceed the computational efficiency of classical semiconductor computer because quantum algorithms allow the execution of certain calculation, such as factoring, in fewer steps. [1]

XI. History of Quantum Computing

When quantum computers were first proposed in the 1970s by theorists such as Richard Feynman of California Institute of Technology, many scientists doubted if quantum computer could ever be made practical. But in 1994, Peter Shor of AT&T came up with an algorithm that can factor large numbers exponentially faster than conventional computers, and the algorithm is now known as the Shor's algorithm. The potential of Shor's algorithm stimulated many scientists to explore the potential of quantum computing.

One of the world's leading experimentalists named Chuang demonstrated the world's first 2-qubit quantum computer in 1998 at University of California at Berkeley. At IBM-Almaden, Chuang and colleagues were first to demonstrate important quantum computing algorithms, which is the Grover's database-search algorithm in 1999 with a 3-qubit quantum computer and later in August 2000 with a 5-qubit quantum computer. About a year after the 5-qubit quantum computer, the factorization by Shor's algorithm were announced in 2001 by using 7 qubits, and the calculation was the most complex algorithm that has been demonstrated by a quantum computer. Having this said, it is interesting to know that the most complicated and the only meaningful calculation performed by the IBM 2001 quantum computer is to factorize the number 15. The IBM 2001 quantum computer was able to correctly find the radicals of 15, which are 3 and 5.

IBM Research is also noted for its many theoretical contributions to the emerging field of quantum information. IBM scientists pioneered quantum cryptography, quantum communications (including the concept of quantum teleportation) and efficient methods of error correction.[1]

XII. Conclusion

The research in the Junior Year Program in English (JYPE) is very rewarding. I am very glad to be able to do research with the 40 million yens, or around 400 thousands dollars, worth of equipments. I have learned a lot through this research. To name a few, writing this final report in LaTeX is a challenge. LaTeX is a whole new programming language to me. Using LaTeX to compile a PDF report needs a lot of time to learn how to make all the necessary symbols needed for the mathematic equations and symbols. In the Research Institute of Electrical Communication (RIEC) laboratory, I learned how scienctific papers and books are usually made out of. I learned the beauty of LaTeX. I also learned ways to generate vector graphic image files. Contrast to the research that I have done in UC Berkeley, the research papers are written in Microsoft Words, and the Microsoft Word files are compiled into PDF files by Adobe Professional. Everything was in a familiar Microsoft Word environment.

Learning Mathematica is another great experience, Mathematica was used to do computations in the laboratory. Mathematica will probably help me solve my math problems after I go back to the United States. Finally, the course material for quantum mechanics was very challenging. I learned a lot from the books about quantum computings and superconductors.

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