PROPERTIES OF METAL-BARRIER-METAL HIGH SPEED TUNNELING JUNCTIONS RESPONDING TO INFRARED AND VISIBLE RADIATIONS

by

GILBERT MICHAEL ELCHINGER

B.S., University of Missouri - Rolla
(1972)

SUBMITTED IN PARTIAL FULFILLMENT OF THE

REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

July 1978

Signature of Author..

Certified by..............................
Thesis Supervisor

Accepted by..
Chairman, Departmental Committee
on Graduate Students

PROPERTIES OF METAL-BARRIER-METAL HIGH SPEED TUNNELING JUNCTIONS RESPONDING TO INFRARED AND VISIBLE RADIATIONS

By

GILBERT MICHAEL ELCHINGER

Submitted to the Department of Physics on July 17, 1978, partial fulfillment of the requirements for the degree of Doctor of Philosophy.

Abstract

The conduction mechanisms of metal evaporated tunnel junctions are examined for applied electric field frequencies from RF to the visible. For optical frequencies, responses were measured when a laser source directly illuminated the junction. Responses of both normal and superconducting junctions were measured.

In the metal-oxide-metal junction, two frequency dependent regimes of conductivity exist. At RF, where the frequency is smaller than the junction's $(RC)^{-1}$ the conduction scheme is electron tunneling. At photon energies in the range of the tunnel barrier height the conduction scheme is photo-induced tunneling. Expressions for the tunnel barrier parameters (width, height, and asymmetry factor) in terms of the RF rectified response are derived from the tunneling formalism. It is shown that the tunnel current, for photo-induced tunneling, is a function of the barrier shape through the energy dependent tunneling probability function. Tunneling theory is used to derive the photocurrents, as a function of incident photon energy, for different barrier shapes; square, trapezoidal, parabolic, and image force lowered. Estimates of barrier shapes for three junctions (Al-Mg, Al-Al, and Mg-Mg) were obtained by matching measured photocurrents to those calculated from the barrier models. Barrier parameters obtained from RF rectification measurements were used as bounds for the barrier models.

Responses to optical fields of the Al-Pb, metal-oxide-superconducting junction were found to be of two types; the thermal, or heating response, and a rectification-like response. The nonthermal responses were found to be independent of radiation frequency, and closely resemble the RF rectified response of the junction. Examination of the nonthermal response characteristics shows that rectification at optical frequencies does not occur. A conduction scheme based on a laser-induced nonequilibrium electron distribution in the superconductor is presented. This model is an extension of a recently proposed model explaining the conduction scheme in superconductor-superconductor junctions. The model proposes that a population inversion of electrons and holes exists about the edges of the superconducting gap when the laser illuminates the junction. The response of the junction, as a function of bias, changes sign at $V_b = \Delta_{Pb}/e$, resembling the rectification response.

Thesis Supervisor: Ali Javan

Title: Professor of Physics

To my parents,

Gilbert and Marion Elchinger

Acknowledgements

I am most indebted to Professor Ali Javan for his valuable advice and support during my studies at M.I.T.

I have had the good fortune to work with Antonio Sanchez for over four years. During this time he has been my teacher, counselor, and lab partner; masterful and meticulous, but always patient. I owe him my deepest gratitude for his support on, and encouragement to pursue, important issues of this thesis.

Professor Judy Bostock contributed many hours of very valuable descriptions of the superconducting junction. These discussions helped to elucidate the superconducting junction response to visible radiations.

The efforts of Bill Ryan and Mary Donoghue to buy, borrow, and steal essential apparatus for the experimental up are invaluable and appreciated.

George Lui devoted many late evening hours to experimental runs. It was my pleasure to work with him.

Several people have contributed personally to this work through their encouraging suggestions and comments. Charles Davis has cheerfully shared his wisdom on several technical, as well as nontechnical, topics. Richard Forber has helped to put many troubling issues in reasonable perspective. Carolyn Cook contributed common sense suggestions to the experimental process.

Penny Johnson generously devoted her time and energy to type this thesis under a very short time schedule.

Every member of the Laser Lab has been eager to assist in solving technical problems, and has- been more than willing to share valuable apparatus.

Table of Contents

List of Figures

Introduction and Summary

In 1967 the first optical frequency mixing experiment was performed using a high speed adaptation of a microwave rectifying diode; a metal-dielectric-semiconductor point contact diode.[1] This point contact diode was formed by electrochemically etching a thin metal wire, forming a very small point, and lightly contacting this point to the surface of a flat semiconductor. Current flowed through the contact region as a nonlinear function of the electric potential applied across it. This element successfully generated harmonics of microwave radiation mixing them with 337μm radiation. This worked because the whole capacitor-like junction could oscillate at these frequencies.

As the frequency of the radiation was increased above about 85μm it became apparent that the current in the semiconductor had a high frequency limit due to the relatively large free carrier response time. A polished metal post was subsequently substituted for the semiconductor.[2] Infrared frequency mixing experiments using this metal-metal oxide-metal (M-0-M) diode confirmed that the response time was very short, approaching the RC time constant set by resistance and capacitance, or area of contact. This M-0-M point contact diode has proven its ability to mix infrared frequencies as high as 1.5μm,[3] allowing direct and accurate frequency measurements of many laser transitions.

Despite the impressive performance of this device, its instability against vibration has partly prompted a search for a new geometry to replace it. The natural choice as a substitute for the point contact diode is the metal evaporated tunnel junction. This is, effectively, a small capacitor formed by evaporating a thin metal film onto substrate, oxidizing it, and sandwiching this oxide dielectric by overlapping with a second metal film. The shape usually resembles a cross, although other geometries have been formed.[4] The oxide thickness must be small enough to permit electrons to tunnel through it.

Several investigators have studied the response to electric fields of these metal evaporated junctions at low frequencies, where the junction $(RC)^{-1}$ was about that of the radiation frequency, and at higher frequencies.[5,6-9] The hope in most of these investigations was that the conduction mechanism in the evaporated junction be the same as that of the point contact diode, being high frequency rectification. Most of these investigations were performed on M-0-M junctions at temperatures above 77K.

The possibility of using these junctions as detectors of infrared and visible radiations has led to the study described in this thesis. Junctions having both normal and superconducting electrodes were studied at incident electric field frequencies from radio frequency (RF) to the visible. The metal-oxide-superconductor (M-0-S) junction response to

RF is seen to be caused by the same conduction mechanism exhibited in the M-0-M junction at this frequency, namely, rectification from electron tunneling. At higher frequencies, however, the conduction processes in these junctions are much different.

The theory of elastic electron tunneling was applied to rectification data obtained from several M-0-M junctions to determine their barrier parameters; the barrier width, L, average height, φ, and an asymmetry parameter, Δφ. Three junctions, $Al\text{-}Al_2O_3\text{-}Al$, $Al\text{-}Al_2O_3\text{-}Mg$, and Mg-MgO-Mg, exhibited small average barrier heights ranging from 1.97eV to 2.8eV. This method of obtaining the barrier parameters was found to be a convenient and versatile tool.

While the low frequency response is governed by electron tunneling through the oxide potential barrier in M-0-M junctions, at large enough photon energies the response was found to be caused by photo-induced tunneling. The photo-current is determined by the transition probability across the barrier as a function of energy. Plots of incident photon energy versus photocurrent revealed a rapidly decaying photocurrent as hν decreased below the barrier height. The shape of this plot is related to the shape of the potential barrier near the top through the penetration probability.

The photoresponse of three junctions exhibiting low barrier heights (Al-Al, Al-Mg, and Mg-Mg, discussed above) was measured using photon energies from 2.04eV to 2.73eV Fowler plots were used to determine a maximum height, φ_2. A model of photo-induced tunneling was applied to both the measured photoresponse data and barrier parameters of each junction to characterize the actual tunnel barrier shape. To facilitate the calculation, probability functions for several model barrier shapes were used to calculate the expected photocurrent, using as constraints the measured barrier parameters, L, φ, $\Delta\varphi$, and φ_2. The barrier models were those that gave analytic expressions for the tunneling probability as a function of energy. These are the square, parabolic, and trapezoidal barriers, and Simmon's image force lowered barrier, approximating a region near the top as parabola.

It was found that specific barrier shapes led to calculated photocurrents matching closely the measurements taken from the Al-Mg and Al-Al junctions. Other barrier shapes conforming to the measured quantities L, φ, $\Delta\varphi$, and φ_2 did not predict the observed photocurrents, confirming that the shape of the barrier determines the junction's characteristic response to radiation energies greater than φ. In the Mg-Mg junction, the calculated photocurrent was independent of the barrier shape for the optical energies used. This is described by the electron tunneling model, which states that for energies less than φ (which is the case for the Mg-Mg junction) the tunneling probability function is determined by φ and not φ(x), the barrier shape near the top. The observed agreement of the barrier parameters to the photo-induced tunneling data confirms that the barrier parameters found at low frequencies are the same ones determining tunneling properties of the junction at visible frequencies.

The M-0-S junction responses to optical fields were found to be of two broad types; thermal or heating, and non-equilibrium.[10] Thermal and non-equilibrium here refer to the electron distributions within the junction electrodes in the presence of the optical field. It was found that response versus bias curves for infrared and visible frequencies closely resemble the rectification response of the same junction. Optical rectification was excluded as the conduction mechanism, for the response was found to exist when the laser illuminated an optically opaque electrode. The opaque electrode blocked the electric field from reaching the barrier. A new conduction mechanism is proposed, based on recent work performed using S-0-S junctions. It is proposed that an inversion of empty states and filled states in the superconductor is established at the edges of the superconducting gap. Electron excitation is facilitated by phonons generated in the normal metal side by laser radiation. The filled states at the top of the superconducting gap, called blocking states, are responsible for rectification-like appearance of the response versus bias.

This presentation has two major sections: First, the M-0-M junction response to electromagnetic fields is presented in Chapters 1 and 3. In Chapter 1, a background theoretical development of both the rectification and photo-emission processes is given. Typical junction responses resulting from these processes are also given including an example calculation of barrier parameters of an Al-Al junction. Chapter 3 discusses the methods of obtaining the barrier shape from photo-induced currents. First, the generalized treatment of photo-induced tunneling given in Chapter 1 is specified for the four model barrier shapes. Then, photo-currents predicted by these models are compared to the measured values for the Al-Mg, Al-Al, and Mg-Mg, M-0-M junctions. The fit is analyzed and a prediction of the barrier shape is made for each junction. Chapter 2 describes the experimental arrangement used to measure both the M-0-M and M-0-S junctions responses.

The second section describes the superconducting junction response to electromagnetic fields, and is contained in Chapter 4. In the first section the rectification response is discussed. This is followed by an analysis of the thermal response, and finally the non-equilibrium, rectification-like response in the remaining two sections.