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# Understanding the Behavior of Superconductors by Analyzing Permittivity

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***Abstract*—**A superconductor has the ability to conduct electricity perfectly and exclude magnetic fields from its interior. In order to understand electromagnetic characteristics of superconductors, their material properties need to be examined. To facilitate this understanding, a theoretical model based on concepts of electromagnetics is presented to explain the electrical and magnetic properties of superconductors. The permittivity response is the key aspect of the model and it describes the electrical resistance response and why it vanishes at the material's critical temperature. The model also explains the behavior of magnetic fields and why they cannot exist inside superconducting materials. The theoretical concepts and equations associated with this model are used to demonstrate that they are sufficient in describing the behavior of both type I and type II (or high temperature) superconductors. This model is also able to explain why superconductors behave differently than perfect conductors. As a result, examining the permittivity response and understanding electromagnetic field theory provides insight into the major aspects associated with superconducting materials.

***Keywords*—**Ampere's law, permittivity, permeability, resistivity, Schrödinger wave equation.

## I. Introduction

SUPERCONDUCTIVITY is a phenomenon in which a material's electrical properties or characteristics change when the temperature reaches a sufficiently low temperature. At this temperature, known as the critical temperature, a superconductor's electrical resistance reduces to zero and the magnetic field inside the material becomes zero [1]-[5]. Currently, research is underway to develop materials that superconduct at room temperature.

One of the goals of science and engineering is to understand how to transmit energy or information efficiently and reliably. Since elevated electrical resistance negatively affects energy and information transmission, superconductivity research is especially important. Thus, if research can advance superconductivity and develop room temperature materials, this will be a revolutionary accomplishment [6], [7].

Electrical resistivity is a material property that produces electrical resistance in a material. This resistivity is a function of temperature and typically as a material's temperature decreases, its electrical resistivity decreases [8]. When the temperature decreases, flowing electrons (which constitute current flow) will have less interaction with lattice atoms and thus these electrons will lose less energy. When a superconductor has no electrical resistance, electrons flow through that material unimpeded and thus current can flow indefinitely (or with infinitesimal decay) [9].

The Meissner effect is the phenomenon that leads to the vanishing magnetic field in superconductors (provided that the magnetic field is small enough). This effect leads to the well-known levitating magnet above a superconducting material due to repulsive forces. For small magnetic fields, regardless of whether the magnetic field is present before or after the material is cooled to its critical temperature and regardless of whether the material is a type I or type II superconductor, that magnetic field will be expelled from the interior of the superconductor. For larger magnetic fields, type II superconductors will exhibit a mixed state in which magnetic fields can penetrate the interior of the material [1]-[5].

In order to understand this phenomenon of superconductivity and to advance superconductivity research, comprehensive and accurate models must be developed. To meet this need, several microscopic or atomic theories have been developed [10]. These theories are not entirely correct, but even partially correct theories can aid researchers in their understanding. The BCS theory and the London equations are two of the most successful theories on superconductivity because they explain certain aspects of superconductors. For example, the BCS theory does a good job of describing the behavior of type I materials, but when high temperature superconductors were discovered, the theory became inadequate [11]-[13]. Furthermore, the BCS theory is imperfect and insufficient in explaining several fundamental properties of superconducting materials such as the Meisner effect [11]. Again, a theory does not have to explain every aspect of a material's behavior, but if it cannot explain the fundamental properties, then it is inadequate. Therefore, a comprehensive theory that explains the electromagnetic properties of all superconducting materials is needed.

A theoretical model has recently been developed to explain the relationship between electrical conductivity and temperature [14]. This theory derives a relationship between these two parameters from basic principles and then its accuracy is demonstrated through comparisons to known linear responses from platinum and nickel. However, because that model does not specifically account for superconducting effects, it was supplemented in order to describe electrical conductivity for superconducting materials [15].

Because the model from this prior research only addressed or developed concepts associated with electrical resistivity of superconductors, the research presented herein will explain why superconducting materials have their magnetic properties. This will be accomplished by analyzing conduction electron

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interactions with atoms and then using electromagnetic field theory. Atomic analysis will be used to demonstrate that when the permittivity has certain properties, electrons will move through a material unobstructed (i.e., the material will act as a superconductor and exhibit zero electrical resistance). Then electromagnetic theory will be used to explain the response of superconducting materials to external magnetic fields. Finally, the theory and model are used to explain why perfect conductors respond differently than superconductors.

## II. Theoretical Model

### A. Electrical Resistance Model

A model that describes the electrical resistance for conductors as a function of temperature has been developed [14] and this model has been enhanced to incorporate superconducting effects [15]. Although complete details have been published, a brief summary is provided here.

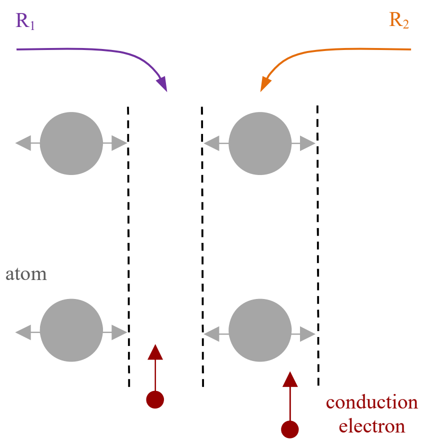



Fig. 1 Illustration of the atomic model showing one electron (small circle) that will be unimpeded by the atoms (large circles) and another electron that may encounter some resistance

The resistance model is developed from a lattice structure that contains atoms and conduction electrons. Atoms vibrate at a rate that is a function of temperature. As temperature decreases, the gap or space between atoms will increase. A higher proportion of electrons in the gap will lead to higher electrical conductivity. A diagram of the model is illustrated in Fig. 1. This model adopts the idea that when an electron is on a path to encounter an atom, that atom could impede the flow of the electron.

Based on Fig. 1, conduction electrons in the gap between atoms will encounter an electrical impedance represented by $R_1$. Likewise, those electrons directly impacted by lattice atoms will encounter an electrical impedance represented by $R_2$. These resistors are in parallel as shown in Fig. 1 and have an equivalent resistance of R.

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} \tag{1}$$

Each resistance can be modeled for specific materials by using the equations in Tables I and II with specified values for the constants (i.e., the C values). Resistance $R_1$ has the same general form for superconducting and non-superconducting materials, however $R_2$ will be different depending upon whether the material is superconducting or not.

TABLE I
EQUATIONS FOR NON-SUPERCONDUCTORS THAT REPRESENT RESISTANCES $R_1$ AND $R_2$ AS A FUNCTION OF TEMPERATURE IN THE RESISTANCE MODEL

| Resistance | Equation |
|---|---|
| $R_1$ | $C_1$ for $T < T_I$<br>$C_2T + C_3$ for $T > T_I$ |
| $R_2$ | $C_4T + C_5$ |

$T_I$ is the temperature at which the resistance of impurities and defects will dominate.

TABLE II
EQUATIONS FOR A SUPERCONDUCTOR THAT REPRESENT RESISTANCES $R_1$ AND $R_2$ AS A FUNCTION OF TEMPERATURE IN THE RESISTANCE MODEL

| Resistance | Equation |
|---|---|
| $R_1$ | $C_1$ for $T < T_I$<br>$C_2T + C_3$ for $T > T_I$ |
| $R_2$ | 0 for $T < T_C$<br>$C_4T + C_5$ for $T > T_C$ |

$T_I$ is the temperature at which the resistance of impurities will dominate, and $T_C$ is the critical temperature at which the material becomes superconducting.

Results show that using these resistance equations will yield results that are consistent with experimental results for superconductors and non-superconductors [15]. But again, to demonstrate that this model adequately describes all superconducting characteristics (i.e., the electrical and magnetic properties), the Schrödinger equation is examined, and electromagnetic field theory is analyzed.

### B. Atomic Model and Permittivity

We consider the lattice shown in Fig. 1 and in particular the region associated with $R_2$. This represents the region of the lattice structure that contains atoms and conduction electrons. Under normal circumstances, the atoms offer electrical resistance to the conduction electrons. However, when a superconducting material reaches its superconducting or critical temperature, the atoms appear to be 'invisible' to conduction electrons. As a result, the electrical resistance disappears, and conduction electrons will be able to travel through the lattice unimpeded.

The electrical resistance of the system can be understood after applying the Schrödinger wave equation to the conduction electrons in the periodic atomic lattice. This analysis and subsequent analysis will reveal why the superconducting and non-superconducting effects occur.

In general, the conduction or traveling electron can be characterized by the Schrödinger wave equation

$$-\frac{\hbar^2}{2m}\frac{\partial^2\psi(x,t)}{\partial x^2} + V\psi(x,t) = i\hbar\frac{\partial\psi(x,t)}{\partial t} \tag{2}$$

where $V$ represents the potential energy that a traveling electron will encounter at some instant in time. Because there are many electrical charges in this model or system, the potential energy can be represented by

$$V = \sum \frac{qQ}{4\pi\varepsilon x} \tag{3}$$

where $q$ is the charge of a traveling electron, $Q$ represents the charge of a nearby object (e.g., nucleus or another electron), $\varepsilon$ is the permittivity or dielectric constant, and $x$ is the distance between the traveling electron and nearby object. In general, there are many moving charges in this model, and thus the exact solution to (2) can be quite complex.

Under general conditions, the potential energy can be determined, and the Schrödinger equation can be solved (regardless of how complex and difficult as that may be). However, when the potential energy becomes zero, the Schrödinger wave equation reduces to

$$-\frac{\hbar^2}{2m}\frac{\partial^2\psi(x,t)}{\partial x^2} = i\hbar\frac{\partial\psi(x,t)}{\partial t} \tag{4}$$

which is the equation for a free electron. As a result, the electron will travel unimpeded [1]. The potential will become zero when the permittivity $\boldsymbol{\varepsilon}$ becomes infinitely large. This is the condition that leads to superconductivity and is summarized in Table III.

TABLE III
CONDITION THAT DETERMINES WHEN A MATERIAL DISPLAYS SUPERCONDUCTIVITY PROPERTIES

| Material Type | Permittivity, $\varepsilon$ |
|---|---|
| Non-Superconductor | Non-zero, finite |
| Superconductor | Infinite ($\infty$) |

### C. Model Summary

The permittivity is the key parameter to understand the electromagnetic properties of superconductors (i.e., vanishing electrical resistance and vanishing internal magnetic field). When the permittivity becomes infinitely large, this will lead to the electrical and magnetic characteristics of superconducting materials. Based on the permittivity, the following sections will demonstrate and/or explain why these characteristics occur for superconductors as well as why superconductors are different than perfect conductors.

## III. Electrical Resistance of Type I Materials

In general, the electrical resistivity for materials is temperature dependent and will linearly decrease with temperature. This general trend is shown in Fig. 2 for both superconductors and non-superconductors [1], [2]. At sufficiently low temperatures, superconductors and non-superconductors will display two different responses. The electrical resistivity for a superconductor will drop abruptly to zero, whereas non-superconductors will display a flat, non-zero response. Accounting for lattice defects such as grain boundaries and impurities, the resistance will have a non-zero value for T~0 and will appear as shown in Fig. 2.

For superconductors, the permittivity will become infinitely large and as a result, the potential energy associated with the atoms in the lattice will become zero. Then according to the Schrödinger wave equation, the conduction electrons become free particles and will experience zero electrical resistance. This confirms that the electrical resistance $R_2$ should be modeled as zero resistance as given in Table II. When the resistances as shown in Tables I and II are used with (1), simulation results are obtained as shown in Fig. 3. This infinite value for the permittivity confirms the electrical resistance model and is the reason why the electrical resistance abruptly drops to zero for superconductors [15].

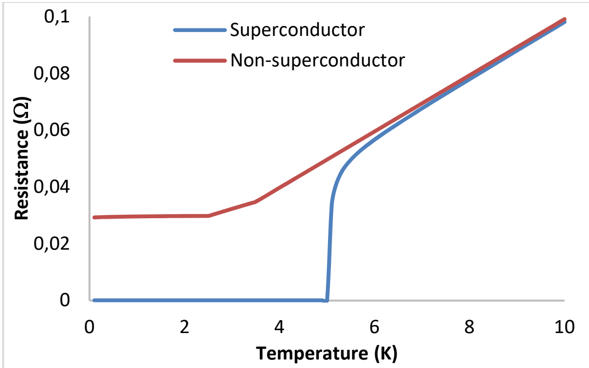
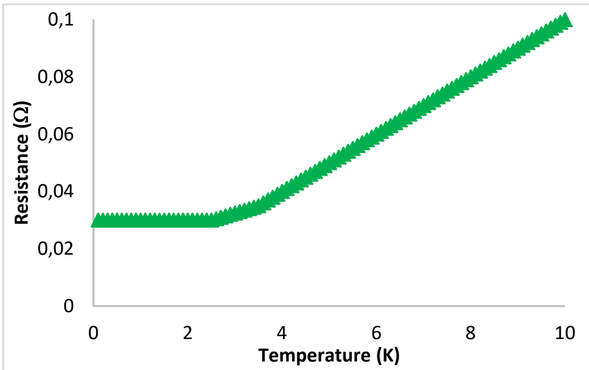
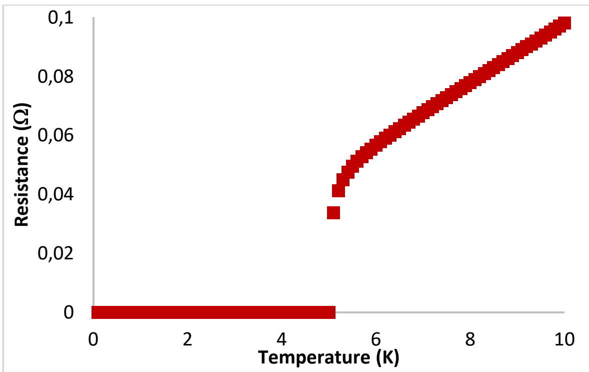



Fig. 2 Example of an experimental electrical resistance response for a non-superconducting material and a type I superconducting material [1], [2]. When the temperature reaches the critical value, the atoms become 'invisible' and the resistance drops to zero. If the material is non-superconducting, a residual resistance from impurities and lattice defects will remain




(a)




(b)

Fig. 3 Simulation of resistances associated with (a) non-superconducting materials and (b) type I superconducting materials

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## IV. Electrical Resistance for Type II Materials

In addition to describing the electrical resistance of type I superconductors, this model can also be used to describe the electrical resistance for type II or high-temperature superconductors. A general graph of the electrical resistance for type II superconductors that is found experimentally is shown in Fig. 4 [16]. This graph also provides an overlay of a type I superconductor (as it would occur at a higher temperature) so that the subtle difference between these two types of superconductors can be observed. It is seen that at the transition temperature where the material goes from normal to superconductor, type I materials transition much faster than type II materials. To account for this transition, the following analysis is used for type II materials. The difference between type I and type II materials is that the permittivity of the atoms will not sharply approach infinity for type II superconductors as it does or type I superconductors. So, instead of producing a permittivity with a sharp response as the temperature approaches the critical temperature, the response will produce a permittivity that gradually approaches infinity near the critical temperature.

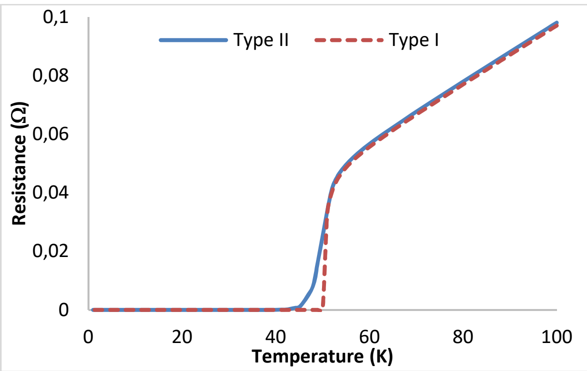


Fig. 4 Example of an experimental electrical resistance response for a type II superconducting material [16]. The response of a type I superconductor is also provided to contrast the sharpness of transition at the critical temperature

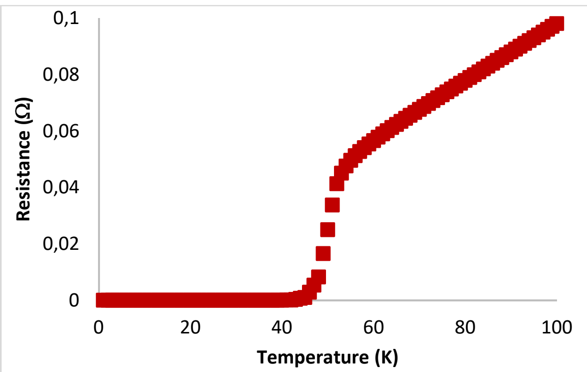


Fig. 5 Simulation of resistances associated with a type II or high temperature superconductor.

If the permittivity does not have a sharp transition to infinity, then electrical resistance $R_2$ should be modeled likewise. When the resistance as shown in Table II is modified to have a wider transition range at the critical temperature, simulation results using (1) are obtained as shown in Fig. 5. This equivalent resistance is typical of type II resistances that are found experimentally [16]. This result confirms the electrical resistance model can accurately describe the response of type II superconductors [15].

## V. Magnetic Fields for Type I Materials

In order to perform magnetic field analysis on superconductors, electromagnetic field theory will be considered and the permittivity concept from the theoretical model will be incorporated into this analysis.

Maxwell's equations can be used to understand much of the interaction between electric and magnetic fields as well as the interaction between these fields and matter [17]. So, to understand why the Meissner effect occurs in superconductors, Ampere's law will be of primary interest. In equation form

$$\nabla x\bar{B} = \mu\left(\bar{J} + \varepsilon\frac{d\bar{E}}{dt}\right) \quad (5)$$

where $B$ is the magnetic flux, $\mu$ is the permeability of the material, $J$ is the current density (and $\bar{J} = \sigma\bar{E}$), $\varepsilon$ is the permittivity of the material, and $E$ is the electric field. In essence, this equation shows that a magnetic field is produced from a current and from a time changing electric field.

In addition to using Ampere's law as shown in (5), other electromagnetic equations and concepts will be used on the basis of the interdependence of electric and magnetic fields, such as Maxwell-Faraday's equation or equivalently $\nabla x\bar{E} = -\frac{d\bar{B}}{dt}$, and the force on charged particles due to external fields or equivalently $\bar{F} = q(\bar{E} + \bar{v}\, x\, \bar{B})$.

Equation (5) shows that the magnetic field is related to the electric field (or the time derivative of the electric field), but it also shows a relationship with the material's permittivity. Because the material's permittivity will behave as described in the previous section of this paper, the two main properties of materials in the superconducting state (i.e., zero electrical resistance and zero magnetic field) will be coupled.

The magnetic fields in the interior of superconductors (and non-superconductors) will now be analyzed. It is first noted that when the temperature of the material is above its critical temperature, superconducting materials will behave as other materials. Therefore, if a magnetic field is applied, this field can exist in the material's interior. It is noted that regardless of the temperature, non-superconducting materials will allow magnetic fields to exist in their interior. However, upon cooling the superconductor to a temperature below its critical temperature, regardless of whether a magnetic field is applied before or after cooling, the material should have an interior magnetic field that is zero [1]-[5]. The two cases of applying the magnetic field before and after cooling will be analyzed. It is noted that to simplify the analysis, it is assumed that there is no initial current flowing through the superconductor, and thus the current density $J$ in (5) is zero. However, it can be shown

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that the presence or absence of an electrical current will not affect the magnetic field analysis/result.

The case of applying the magnetic field after cooling the superconductor below its critical temperature is examined first. For the area where there are atoms, the permittivity $\varepsilon$ will be infinite and initially since there are no fields present, the electric field will be zero and thus *dE/dt* will be zero. Now, when a magnetic field is applied to the material, the magnetic field changes in space and time from a value of zero to a value that is non-zero and finite. Therefore, $\nabla x B$ will be non-zero. This changing magnetic field will produce a changing electric field and thus *dE/dt* will become non-zero and finite. As a result, ($\varepsilon$)(*dE/dt*) will be infinite. In order for (5) to be true, ($\mu$)($\varepsilon$)(*dE/dt*) must be finite and this will only be true if the permeability becomes zero or $\mu = 0$. If $\mu$ is zero, then there will be no magnetic flux in the material. In essence, conduction electrons on the surface of the material will circulate according to equation $\bar{F} = q\bar{v}\, x\, \bar{B}$ and produce magnetic fields that will cancel the external field such that there will be no net magnetic flux inside the material. (It is noted that technically speaking, the magnetic field will not become abruptly zero into the material, but it will decay exponentially according to the London penetration depth [1], [2], [18].) If or when the external magnetic field is removed, the conduction electrons stop circulating and return to their normal linear motion. The superconducting material will retain its permittivity and permeability values and eventually return to equilibrium if there is a disturbance. If the external magnetic field becomes too large, it will stretch and alter the atoms in the material. As a result, the surface current will be affected and additionally the permittivity $\varepsilon$ of the atoms will no longer be infinite. Thus, the permeability $\mu$ will no longer be zero and therefore, the magnetic field will be able to penetrate the material.

Next the case of applying the magnetic field before the superconductor is cooled below its critical temperature is examined. Initially, the permittivity $\varepsilon$ is non-zero and finite, the permeability $\mu$ is non-zero and finite, and the magnetic flux *B* inside the material is non-zero and finite. Now, when the material reaches the transition or critical temperature, the permittivity changes from a non-zero finite value to infinite. As a result, electrons travelling in the path of atoms will circulate to counteract the applied field according to $\bar{F} = q\bar{v}\, x\, \bar{B}$. These circulating charges will change or reduce the external magnetic field. As a result of the changing magnetic flux, a changing electric field *E* will be produced, so *dE/dt* will be non-zero. Since $\nabla x B$ will now be non-zero and finite, then ($\mu$)($\varepsilon$)(*dE/dt*) must be finite. This can only happen if the permeability becomes zero or $\mu = 0$. If $\mu$ is zero, then there can be no magnetic flux in the material or $B = 0$, so the field will get expelled from the superconductor. Again, when the external magnetic field is removed, the conduction electrons stop circulating and return to their normal linear motion. The superconducting material will retain its permittivity and permeability values and eventually return to equilibrium if there is a disturbance. Also, when the external magnetic field becomes too large, the atoms and surface current will be altered, and the superconducting properties will be destroyed (so the resistivity is no longer zero and magnetic fields can penetrate the material).

Now it is noted that the current density $J$ ($=\sigma E$) in the superconducting material cannot be infinite, so as the conductivity $\sigma$ becomes infinite (or equivalently as the resistivity becomes zero), the electric field $E$ must become zero in the superconductor. The converse is also true because if $E$ is zero, then a non-zero current density can only be produced if the conductivity $\sigma$ is infinite. This will produce a finite current density which could be zero or non-zero. The magnetic field analysis was performed using a current density of zero. However, if the current is non-zero and finite, the results are still the same because for those cases where ($\varepsilon$)(*dE/dt*) was infinite (J + $\varepsilon$ *dE/dt*) will still be infinite and for those cases where ($\varepsilon$)(*dE/dt*) was finite (J + $\varepsilon$ *dE/dt*) will still be finite.

## VI. Magnetic Fields for Type II Materials

The procedure for determining the state of the magnetic field in type II superconductors is very similar to the approach developed for type I materials. However, type II materials will produce a slightly different response than type I materials. As previously stated for type I superconductors, when the temperature reaches the critical temperature, the permittivity $\varepsilon$ becomes infinite (and this equivalently produces an infinite conductivity or zero resistivity). This leads to circulating conduction electrons producing a magnetic field to cancel the external magnetic field and that leads to the permeability $\mu$ becoming zero. Thus, magnetic flux will be excluded from the material provided that the applied magnetic field is below the critical level (which is temperature dependent). When the magnetic field exceeds this critical magnetic field, the material will return to its non-superconducting state and allow magnetic flux to penetrate its interior [1]-[5]. This same process occurs for type II materials; however these superconductors have two critical magnetic fields. If the applied field is less than the lower critical magnetic field, the type II material behaves as a type I material and excludes all of the magnetic flux from its interior. If the applied field is greater than the upper critical magnetic field, the type II material also behaves like type I materials and will allow the entire external field to penetrate its interior. However, when the applied field is between the upper and lower critical values, only a portion of the external field will penetrate type II materials. This is called the mixed state in which there are superconducting and non-superconducting regions in the material [1]-[5]. Type II materials behave this way because its atoms will be stretched and altered due to the magnetic field. Based on the state of the surface current and the state of the permittivity of the atoms in the material, the three different states of type II superconductors (i.e., superconducting, mixed, and normal) can be explained. As long as the external magnetic field is smaller than the lower critical field, surface currents will exist, and the permittivity of the atoms will be

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infinite and the material will exist in the superconducting state. This response is similar to type I materials, so no additional analysis is necessary.

The permittivity of the atoms in the material will vary as a function of the magnetic field (as well as temperature). So, when the external magnetic field becomes large and exceeds the lower critical field, the permittivity $\varepsilon$ will not be infinite (but it will still be very large) and based on Ampere's law, the permeability $\mu$ will no longer be zero. So, a magnetic field will be able to exist in the material. The surface currents will remain until the magnetic field reaches the upper critical field. These surface currents will block out most of the magnetic field but will allow some of the external field to penetrate through the surface. Again, since the permeability is not zero, the magnetic field will be able to exist in the interior of the material. This creates a pattern of superconducting and non-superconducting regions and forms an Abrikosov lattice [19]. This is the mixed state.

Finally, if the magnetic field is continually increased and reaches the upper critical field, the atoms in the material become stretched to the point where they interfere with the surface currents. Since the surface currents will no longer be able to flow unimpeded (and the permittivity of the atoms is no longer infinite), the material moves from a mixed state to a completely non-superconducting state.

## VII. Superconductors and Perfect Conductors

The theoretical model presented in this paper can also explain why perfect conductors are different than superconductors. The main difference between a perfect conductor and a superconductor lies in their response when a magnetic field is applied before the material is cooled to its transition temperature. A superconductor will exclude the field when the transition temperature is reached but the perfect conductor will allow the magnetic field to remain [16], [20]. Based on the theoretical model, the magnetic field response for a superconductor has been explained using Ampere's law. For the perfect conductor, a similar analysis will be performed.

The characteristic property for a perfect conductor is $\sigma = \infty$ when the material is below the transition temperature (compared to $\varepsilon = \infty$ for superconductors). However, the other parameters of the perfect conductor, $\varepsilon$ and $\mu$, remain normal. Since $\sigma = \infty$ and $J = \sigma E$, the electric field $E$ must vanish in the material to keep the current density $J$ finite. Thus $dE/dt$ must be zero. Using Ampere's law for perfect conductors, the term $(\mu)(\varepsilon)(dE/dt)$ will be zero since the first two terms are finite and dE/dt is zero. Since $\nabla x B$ and $(\mu)(\varepsilon)(dE/dt)$ must be equal, $\nabla x B$ must be zero and thus $B$ cannot change spatially. If a magnetic field is present in the material, it will remain in the material so, $\mu$ will be non-zero and finite; however, if the material is cooled first, a magnetic field cannot enter the material, so $\mu$ will be zero. The materials parameters are summarized in Tables IV and V. Since this is how perfect conducts respond, this model properly explains this phenomenon.

TABLE IV
MATERIAL PARAMETERS FOR TYPE I SUPERCONDUCTORS AND PERFECT CONDUCTORS WHEN THE MAGNETIC FIELD IS APPLIED BEFORE THE MATERIAL IS COOLED

| | Superconductor | Perfect Conductor |
|---|---|---|
| Permittivity, $\varepsilon$ | Infinite ($\infty$) | Non-zero, finite |
| Permeability, $\mu$ | Zero (0) | Non-zero, finite |
| Conductivity, $\sigma$ | Infinite ($\infty$) | Infinite ($\infty$) |

TABLE V
MATERIAL PARAMETERS FOR TYPE I SUPERCONDUCTORS AND PERFECT CONDUCTORS WHEN THE MAGNETIC FIELD IS APPLIED AFTER THE MATERIAL IS COOLED

| | Superconductor | Perfect Conductor |
|---|---|---|
| Permittivity, $\varepsilon$ | Infinite ($\infty$) | Non-zero, finite |
| Permeability, $\mu$ | Zero (0) | Zero (0) |
| Conductivity, $\sigma$ | Infinite ($\infty$) | Infinite ($\infty$) |

## VIII. Discussion

A model has been developed that demonstrates and explains why some materials become superconducting (at sufficiently low temperatures) and display the corresponding electrical and magnetic properties, and why other materials do not. The model produces results in which electrical resistance is a function of temperature and it explains why magnetic fields can or cannot exist in these materials. These theoretical results are consistent with experimental results and this is true whether the material is classified as a type I superconductor, type II superconductor or a non-superconductor.

The model leads to a permittivity that will allow electrons to travel in the presence of atoms without losing energy if the material's temperature is sufficiently low. This creates a material where conduction electrons can travel unimpeded because there are no 'obstacles' or potentials for electrons to overcome.

Using a classical approach to analyze atoms in a material, it can be shown that atoms have a resonant frequency and a permittivity that is dependent upon this resonant frequency [17]. If the frequency of conduction electrons matches the resonant frequency of the atoms, the permittivity will become infinitely large and as a result, this will lead to the material displaying superconducting properties.

It is noted that atoms will have a temperature dependent frequency response since energy (and thus an atom's motion) and temperature are directly related [21]. Based on properties of atoms and the relationship between material parameters, structures can be designed and created to meet required specifications. Specifically, the temperature and frequency relationship of atoms can be used to engineer devices to operate under certain conditions [22].

At sufficiently low temperatures, some materials display superconducting effects and others do not. Materials that do not have superconducting characteristics will display normal electrical resistance. This normal response is demonstrated by an electrical resistance that has a linear response except when the temperature is near zero [1]-[5]. At these low temperatures, the resistance (or resistivity) will be constant or temperature independent. This residual resistance is a function of the purity of the material and/or the number of lattice

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imperfections [1].

For superconductors, the electrical resistance is linear when temperatures are above the critical temperature, zero when temperatures are below the critical temperature, and has a transition region at the transition temperature. For type I materials, the transition is almost instantaneous and occurs within $10^{-3}$ K, whereas for type II materials the transition occurs on the order of 1 K [17]. It is noted that the value and slope of the transition to zero resistance can be affected by purity and isotopes [17], [23], [24]. Because the response of type II materials seems to be more prone to these types of effects, they can be viewed as type I materials that are either impure materials or composite materials. Therefore, it is reasonable to obtain the response of type II materials by altering the characteristics of type I materials in the theoretical model.

Many type II superconductors are composite materials, so it is expected that the permittivity of these materials (and the resonant frequency) has a complex response. In other words, since the structure and composition for type II materials is typically more intricate than type I materials, a more complex response would be predicted. Analysis of the model suggests that the permittivity of type II materials does not immediately become infinitely large at the transition temperature (like type I materials), but rather it gradually transitions to infinity.

This theoretical model can account for the magnetic field properties associated with superconductors (i.e., the Meissner effect). If a material behaves as a superconductor, its permittivity becomes infinitely large when its temperature goes below the critical temperature. As a result, Ampere's law will require that the material's permeability go to zero and therefore the material must exclude magnetic fields. So, these two properties will accompany one another.

This model can also account for the mixed state in type II superconductors in which the magnetic field can exist in a portion of the material. This mixed state can exist because when the magnetic field is strong enough, the permittivity of the atoms diminishes and ceases to be infinite. As a result, perpetual currents cannot exist in the bulk of the material to shield the external magnetic field. However, there are surface currents that exist 'above' the atoms in the material and those perpetual currents will shield some of the external field. The potion of this field that penetrates this shield will then be allowed to exist inside the material.

The relationship between temperature and resistivity has been developed and is understood [25], [26]. Additionally, the relationship between temperature and magnetic field for superconductors is also well known [27], [28]. Because of these relationships, when a magnetic field is applied to a superconductor, that field is expected to cause the electrical resistance to change [29]-[31]. The magnetic field will directly affect the atoms so if it becomes large enough, the field will change (or mask) the resonant frequency and permittivity which will affect the surface currents.

## IX. Conclusion

A theoretical model has been developed to explain why the electrical resistance of some materials (i.e., superconductors) completely vanishes and why they conduct electricity perfectly and thus offer no impedance to electrons. This model also demonstrates why these conductors exhibit the Meissner effect and exclude magnetic fields from their interior. When the permittivity of the materials becomes infinitely large, the superconducting properties are exhibited.

This theory and model are general and flexible enough such that it demonstrates the electrical and magnetic characteristics of all materials regardless of whether they are superconducting or non-superconducting. Yet the theory and model are specific enough so that it can be applied to any superconducting material whether it is classified as a type I or type II. The model also applies to high temperature superconductors. Based on the structure of this model, it distinguishes between the characteristics of superconductors and perfect conductors. Thus, this theoretical model provides insight into the physical mechanisms that cause the electromagnetic properties of the superconductors. Therefore, this model should benefit researchers who are in the process of developing room temperature superconductors.

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