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STUDY OF TRANSPORT PROPERTIES OF SUPERCONDUCTING ALLOY NbN ULTRA-THIN FILM AND EVALUATION OF HALL COEFFICIENT OF SEMICONDUCTOR THIN FILMS

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Abstract :

Thin films of superconductors are of both technological and academical interests. The properties of interacting electrons systems are governed by the electronic density of states (DOS). This DOS changes upon the reducing the spatial dimensions. If one changes dimension 3D-2D, this affect, optical electronic and thermodynamic property of the system. In the superconducting states, quasi 2D system turn out to be particular fruitful film and it lead to remarkable findings such as insulators, featuring **superconducting gap**. Pseudo gap in S-wave conventional superconductor and extremely strong coupling superconductivity in **Kondo-lattice**. Thin film superconductors play a key-role in many applications such as SQUIDS, Thermal-electrical switching using Josephson Junction and microwave resonator. Ultra thin film of NbN gives very useful results. We have shown the optical constants and superconducting properties of NbN thin film for different values of thickness d(nm). Our evaluated results show that for small wavelength s_1 is positive and as wavelength increases, s_1 crosses from positive to negative values. The negative values increase for large wavelength. We repeated the calculation for imaginary part of the dielectric constant s_2 as a function of wavelength (nm) for different values of NbN film thickness d(nm). We have shown the evaluated results of energy gap parameter $2\Delta(T)$ as a function of temperature T(K) for NbN ultra thin film for $T<T_C(K)$. $T_C(K)$ for NbN thin film we have studied theoretical and evaluated the transport properties of superconducting NbN ultra thin films.

Key words : superconducting gap, Kondo-lattice, dielectric constant, transport properties, transition temperature, spectral ellipsometry, non-photonics, Hall coefficient.

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INTRODUCTION

In this paper we have theoretically studied electro dynamics and evaluated superconducting and optical properties of ultra thin film at THz frequencies. Our theoretically evaluated results of real and imaginary part of complex optical conductivity $\square_1$ and $\square_2$ as a function of (2O(T)/ħm) for different temperature and fixed film thickness show that both $\square_1$ and $\square_2$ decrease with the function (2O(T)/ħm) for all the temperature taken. Our theoretically evaluated results of superconducting transition temperature T_C (K) increase with film thickness d. Our theoretically obtained results of real and imaginary part of dielectric constant s_1 and s_2 as a function of wavelength and fixed film thickness indicate that s_1 decrease with wavelength and crosses positive and negative value as wavelength increases. However the value of s_2 increase with wavelength for all film thickness d and its values are always positive.

Our evaluated results of absorbance as a function of wavelength for different film thickness decrease with wavelength. Our evaluated results of real and imaginary part of the impedance for all film thickness 5.6 nm indicate that real part of the impedance □ increase while imaginary part decrease with wavelength. Our evaluated results of temperature dependent upper critical field B_{C2} (T) for different film thickness decrease Our evaluated results of density of states at the Fermi level N_0 as a function of film thickness increase with thickness d. Our evaluated results of energy gap parameter 2A(T) mev as a function of temperature for NbN and TaN film decrease with T and becomes zero at T=Tc. The results are in accordance with the BCS theory. Our evaluated results of the ratio $\frac{2\Delta(0)}{K_b T_C}$ as function of T_C in the vicinity of T_C show anomalous behavior. The ratio is 4.507 for NbN thin film (T_C=12.5K) and 4.082 for TaN thin film (T_C=9.7K) respectively.

Here, we have evaluated superconducting and optical properties at THz frequencies. These were grown on Sapphire and evaluated by means of spectral ellipsometry and dc measurement of superconducting critical temperature. The films are well described by the scattering matrix method and with BCS and Drude theory. Our evaluated results are in good agreement with other theoretical workers. These results are quite useful and fruitful in analyzing various devices for nano-photonics.

We have theoretically evaluated transport properties of superconducting NbN ultra-thin film and Hall coefficient and dc conductivity of some semiconductor thin film.

Evaluation of transport properties

Since NbN films generally occupy an intermediate position between good metals like gold or aluminum and a semiconductor, the permittivity for

a film with known thickness is determined as the complex spectral function that provided the best fit to the data of ellipsometry measurements. In general the permittivity of a metal can be presented as a function of the circular

frequency m in the following form[1]

$$s_r = s_{r0} - \frac{m_p^2}{m(m + \mathbf{j}(1/c))} + \sum_q \frac{\Omega_{cq}^2}{(\Omega_{oq}^2 - m^2 - \mathbf{j}\Omega_{Dq} m)} \tag{1}$$

Here s_{r0} is the permittivity at large frequencies, m_p is the plasma frequency, v is elastic electron scattering time which is used as fitting parameter. Intraband transitions active in the ultraviolet and partly in the visible portion

of the spectrum is modeled as a set (q=2) of single oscillators each having its own strength Ω_{cq}, central frequency $\Omega_{oq,}$ and damping $\Omega_{oq,}$. In the near- infrared portion of the spectrum the contributions of these oscillators to the

total permittivity of a good metal should become negligible. One made sure that the thickness d of all studied films was much smaller than the electromagnetic skin depth in the visible and near-infrared that justified the

use of the film impedance $Z_F = Z^C(mds \quad _o \qquad _r)^{-1}$. Here c is the velocity of light

in vacuum, Z_0 is the impedance of the vacuum. These parameters are used for computing the absorbance of non-structured films. Although NbN is a strong-coupling superconductor, for the sake of clarity, one uses BCS theory relations between the transition temperature and the energy gap. NbN films

typically have rather than small electron mean free path 1 and relatively large penetration depth Λ obeying the relation $l \prec \xi_0 \prec \Lambda$. Here ξ_0 is the BCS coherence length. These conditions put them in the limiting case of a dirty superconductor and the local electrodynamics. In this case the diffusivity and

the critical current density at zero temperature is given by[2]

$$D = \frac{1.097}{-\left[\frac{dB_{C2}(T)}{dT}\right]_{T=T_C}} \qquad (2)$$

$$j_c\,(o) = 0.18N_o[10^{47}J^{-1}m^{-3}(T_c)2 \qquad \frac{1}{\ } \qquad (3)$$

Here N_o is the density of the electronic states per one spin at the Fermi level. The critical current density at zero temperature is obtained by fitting the experimental critical current density j_C near the transition temperature with the two-fluid temperature dependence of the depairing critical current density[3]

$$j_C\,(T) = j_C\,(0)\,(1-t^2)\,(1-t^4)2,\ t = \overset{1}{\bar{T}}/T_c \qquad (4)$$

Superconducting parameter for NbN thin films

The total resistivity of the films comes from two contributions. (i) a constant normal-state conductivity $\square_n$ (ii) contribution from superconducting fluctuations of the Aslamasov-Larkin (AL)[4] type, $\square_{AL.}$ The total resistivity then equals q = $1/(\square_n+\square_{AL})$. The fluctuation conductivity $\square_{AL}$ is given by

$\square_{AL}=e^2T_c\,(16\hbar d(T-T_c))^{-1}$. Here d is the film thickness. For comparison with

the optical impedance, one computes the dc resistance of a film square R= R $(295)N^{-1}$ where R(295) and N^{-1} are the resistance of the strip at room temperature and the number of squares respectively. The term RRR is the

residual resistance ratio and is defined as the ratio of film square resistance at temperature 295K and 20K. The other parameters are the following[5-6],

$$K_F l = \hbar(3\pi^2)^{\frac{2}{3}} n_e^{\frac{-1}{3}} (e^2 q_n^{-1}) \qquad (5)$$

Here n_e is the free electron concentration , l is the mean free path, K_F is Fermi wave vector, l is equal to $(3Dv)^{1/2}$

Determination of Hall coefficient Metals

Hall Effect is a direct manifestation of the Lorentz force on the free electron in the solid. Current density in terms of carrier concentration n is given by

$$\vec{J} = ne\vec{v} \quad (5b)$$

$$(\vec{H} = x\vec{v}).e = e\vec{E} \qquad (6)$$

Here, H is the magnetic field, v is the velocity and E is the electric field. From equation (5) and (6), one has

$$E_y = -\frac{1}{n.e} H_z. J_x \qquad (7)$$

The Hall field being proportional to the current density and the magnetic field, it can be written as

$$E_J = R_H.E_z.J_x \qquad (8)$$

Where R_H is a constant known as Hall coefficient. From equation (8) and (6), on has

$$R_H = \pm \frac{1}{nec} \text{ (in cgs unit)} \qquad (9)$$

This equation is used for detecting the carrier concentration. The sign or R_H is positive or negative respectively for holes and electrons. In terms of Hall voltage V_H, equation (8) can be written as

$$V_H/b = R_H H_Z - I/bd\ V_H$$

$$= R_H H_Z - I/d$$

$$R_H = V_H d/IH_Z \qquad (10)$$

Here b d and I are the sample width, thickness and the total current flowing trough it. Another important parameter known is the Hall mobility μ_K is defined as the velocity per unit electric field,

$$\mu_K = R_H a \qquad (11)$$

Where a is the electrical conductivity. The Hall mobility is equal to conductivity mobility, □ only when the relaxation rate v is the function of carrier velocity (or energy) and thus

$$\square = \mu_K/y \qquad (12)$$

$$R_H = \pm y/nec \qquad (13)$$

y is constant which varies according to type of scattering that predominates with the degree of degeneracy in the conduction band. However in most of the cases it does not differ much from unity and the relation $R_H = \pm y/nec$ generally holds good.

Evaluation of Hall coefficient for semiconducting thin film

The Hall coefficient of semiconducting thin film was determined by Van Der Pauw configuration[7]. Here, voltage measurements were taken and two values of resistivity $q_{Æ}$ and q_B were derived using the relation

$$q_{Æ} = (n/In2)\, f_{Æ} t_t((V_1 - V_2 + V_3 - V_4)/4I) \quad (14)$$

$$q_B = (n/In2)\, f_{Æ} t_t((V_5 - V_6 + V_7 - V_8)/4I) \quad (15)$$

Here, $q_{Æ}$ and q_B are resistivity's in ohm-cm. t_t is sample thickness in μcm. V_1-V_8 represents the voltage measured by the Voltmeter. I is the current in amperes passing through the samples. f_A and f_B are geometrical factors based on sample based on sample symmetry. Once $q_{Æ}$ and q_B are known, the average resistivity ($q_{ÆVG}$) can be determined as follows

$$q_{ÆVG} = (q_{Æ} + q_B)^{/2} \quad (16)$$

The Hall signal was measured between two ends while the current was passing through the other two ends. Hall mobility μ is given by the ratio.

$$\mu = \Delta Rx \frac{10^8}{BR_{ch}} \quad (17)$$

Where ΔR is change in resistance due to the magnetic field B which is applied to measure Hall voltage and R_{ch} is the sheet resistance. The resistivity is proportional the reciprocal to the product of the free carrier

concentration n and the mobility μ by the following relation.

$$q = \frac{1}{en\mu} \quad (18)$$

The Hall coefficient R_H is given by

$$R_H = qx\mu \qquad (19)$$

The type of carriers can be understood from the sign of the R_H and thus the type of conductivity can be identified. The negative value of R_H corresponds to the flow of electron (n-type) and positive value corresponds to the flow of holes (p-types)[8]

Results and Discussion

In this paper using the theoretical formalism of A Engel et. al. We have studied the transport and optical properties of NbN superconducting thin films. Using the theoretical formalism of S. Thirumavalavana et al.[9-12], we have studied the Hall effect of semiconducting thin film. In Table-1 we have presented the evaluated parameters of NbN thin films with different thickness. Here we have shown the film thickness d(nm), transition temperature T_c(K), square resistance at room temperature Rs(295k), Normal resistivity $q_n(T>T_c)$, Residual resistance ratio at 295K and 20K (RRR). We observed that as diameter of thin film increases the residual ratio first decreases and than increases. In Table- 2 we have shown the parameters of the single oscillator which are used to obtain best fit for the experimental data with equation (1) Thickness in nm and oscillator frequencies in the units of 10^{15} rad sec^{-1} in Table-3. We have used the remaining parameter of single oscillator which are used to obtain best fit for the experimental data with the equation (1). In Table-4, we have shown the obtained results of Hall coefficient of superconducting thin films. Here d is the thickness, W is the wide stress, free electron concentration ne Ioffe-Regal parameters Kgl and Hall coefficient R_H. We observe that for thickness from 3.2 to 12, the Hall coefficient are negative.[13-20]

In Table-5, we have shown the Hall coefficient for semiconducting thin films. In Table 6 we have shown the Hall coefficient R_H (Cm^2/C) of the different thin semiconducting films. There are some other useful calculation made in this toll ultra thin films semiconducting and superconducting at THz frequencies.[21-37]

Summary

In this paper, we have studied the transport properties of superconducting thin films of NbN using theoretical formalism of spectral elliprometry. We have also obtained the Hall coefficient using equation (1) using the theoretical formalism of S. Thirumavalavana. et al.[9-12], We have studied the Hall coefficient of several semiconducting thin films. The negativeness increases as a function of temperature.

Conclusion

In this paper we have studied the transport properties of different thin films of superconducting and semiconducting thin films. We observed that for semiconducting thin films for theoretical formalism of Eagel et al. works very good and for semiconducting thin films, the theoretical formalism of S. Thirumavalavana et al.[10-12] works very good.

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Table- 1

Transport and optical properties of NbN thin films Film thickness d(nm), Transition

temperature T_C(K), Square resistance at room temperature Rs(295K), Normal resistivity q_n(T>T_C), Residual resistance ratio at 295 K and 20 K (RRR)

d(nm)	TC(K)	Rs(2955)□	q_n(T>T_C) µΩN	RRR
3.2	9.87	707	2.66	0.830
3.5	10.84	688	2.76	0.823
3.9	11.84	572	2.71	0.824
4.3	12.44	478	2.40	0.856
5.1	13.23	341	1.91	0.934
5.3	11.54	261	1.46	0.950
5.6	12.95	280	1.70	0.922
5.8	13.56	265	1.65	0.932
6.7	13.42	145	1.97	1.001
8.0	13.99	191	1.56	0.979
8.3	14.40	165	1.44	0.950
11.7	15.20	150	1.25	0.980
14.4	15.57	84	1.17	1.033

Table 2

Parameters of the single oscillator which were used to obtain best fit for the experimental data with equation (1). Thickness in nm and oscillator frequencies are in units of 10^{15} rad sec^{-1}.

d	$^{s}r0$	Ω_{01}	Ω_{c1}
3.2	2.58	9.58	21.73
5.8	2.58	9.58	21.73
8.3	2.58	9.58	21.73
12	2.58	9.58	21.73
15	2.58	9.58	21.73

Table - 3

Parameter of the single oscillator which were used to obtain best fit for the experimental data with equation (1). Thickness is in nm and oscillator frequencies are in units of 1015 rad sec-1.

d	Ω_{D1}	Ω_{02}	Ω_{c1}	Ω_{D2}
3.2	7.08	1.32	6.83	2.42
5.8	7.08	1.68	8.85	3.03
8.3	7.08	1.78	8.85	3.27
12	7.08	1.89	7.80	3.27
15	7.08	2.26	4.74	2.95

Table -4

Determination of Hall coefficient of superconducting thin films

Hall coefficient RH, Thickness d, Wide streps W, Free electron concentration ne, Ioffe-Regel parameters kFl.

d(nm)	T_C(K)	W(μN)	$n_e(10^{23} m^{-3}$	$k_F l$	$R_H(10^{-11 m3} C^{-1})$
3.2	10.72	10	2.59	2.62	-2.406
6	14.02	10	1.26	5.56	-4.961
12	15.12	5	1.26	5.65	-4.983

Table -5

Determination of Hall coefficients for semiconducting thin films.

Hall effect parameters for prepared thin semiconducting films

Sample	mobility □ (cm^2/Vs)	Resistivity(q)ΩcN	Activiationenergy (Ea) (eV)
CuSe	17	6.24×10^{-4}	0.040
CdSe	88	3.25×10^{4}	0.350
ZnSe	14	4.45×10^{3}	0.252
PbS	47	4.25×10^{2}	0.404
ZnS	63	1.73×10^{4}	0.602
CdS	61	4.36×10^{4}	0.324

Table 6
Hall Effect parameters for prepared semiconducting thin films

Sample	Carrier Concentration (n)/cm^2	Conductivity a(ΩcN)	Hall coefficient R_H(cm^2/C
CuSe	5.2×10^{20}	1.60×10^{-5}	1.05×10^{-2}
CdSe	1.165×10^{12}	2.98×10^{-5}	2.95×10^{6}
ZnSe	8.83×10^{13}	2.24×10^{-4}	6.23×10^{4}
PbS	2.14×10^{13}	2.35×10^{-3}	1.49×10^{4}
ZnS	5.36×10^{12}	5.38×10^{-5}	1.08×10^{6}
CdS	4.23×10^{12}	2.29×10^{-5}	2.15×10^{6}

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