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EFFECTS OF SPACE PLASMA DISCHARGE ON THE PERFORMANCE OF LARGE ANTENNA STRUCTURES IN LOW EARTH ORBIT

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EFFECTS OF SPACE PLASMA DISCHARGE ON THE PERFORMANCE OF LARGE ANTENNA STRUCTURES IN LOW EARTH ORBIT

by

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Summary

The anomalous plasma around spacecrafts in low earth orbit represents the coma of an artificial comet. The plasma discharge is caused by an energetic disturbance of charged particles which were formerly in a state of equilibrium. The plasma can affect the passive and active radio frequency operation of large space antennas by inducing corona discharge or strong arcing in the antenna feeds. One such large space antenna is the 15-meter hoop column antenna which consists of a mesh membrane material (tricot knitted gold plated wire) reflector and carbon fiber tension cords. The atomic oxygen in the plasma discharge state can force the wire base metal particles through the gold lattice and oxydize the metal particles to build a Schottky-barrier contact at the point where the wires meet. This effect can cause strong deviations in the reflector performance in terms of antenna pattern and losses. Also, the carbon-fiber cords can experience a strength reduction of 30 percent over a 40-hour exposure time.

Introduction

The change of space flight emphasis from deep space to low earth orbits (LEO) with the space shuttle and space station, has left the aerospace community with several unresolved problems associated with the utilization of large structures for space communications, navigation, remote sensing and extra-vehicular activities (EVA). This is due to the contamination and ambient environment of LEO with a variable concentration of charged particles. These particles are initially in a state of equilibrium. However, a disturbance from a moving spacecraft in LEO can cause phenomena such as plasma glow discharge, whistler waves, static discharges, and charge effects on the surface of space vehicles.

The implications in the operation of space shuttle and space stations are numerous. This paper describes the characteristic of plasma discharge in LEO and discusses the effects on passive and active operation of antennas. A more detailed analysis is directed toward the glow discharge and temperature variation effects on the material of mesh membranes and cords of a hoop-column type antenna.

The Characteristic of Space Plasma Discharge

The ambient environment of the ionisphere starting at 50 Km above the earth surface and reaching out into space consists of solar flux, ambient gas species, energetic cosmic rays and plasma ions and electrons. For low earth orbits between 200 and 1000 Km the plasma ions and electrons are the potential contribution to discharges (ref. 1). Table I shows the ambient atmosphere concentration of various gas species in the form of molecular or atomic charged particles for the low earth orbits of 200, 300, and 800 Km altitude (ref. 1). One of the most active particles is atomic oxygen which, together with surface contamination, attacks the surface of spacecrafts more aggressively than other constituents. The density of atomic oxygen in atoms per cm^3 at low earth orbit altitudes is shown in fig. 1 (ref. 1). Fig. 1 indicates the changes of concentration with solar activities such as sun spots and flares. The critical ionization velocity required to initiate strong plasma emission of optical and infrared waves is 12.7 Km/sec (ref. 2). This velocity dependency is explained in detail in ref. 2 and is based on the so-called Alfven critical ionization.

The spacecrafts Gemini, Skylab and Shuttle experienced strong glow plasma discharges inspite of their approximate 8 Km/sec orbit speed. This was due to the compacted higher density of charged particles (shorter mean-free-path) at the ram side of the spacecraft and the counter streaming of reflected charged particles. The experienced glow discharge in the wake of a moving spacecraft depends on the disturbance of the ambient by turbulence coming from the ram section, degasing of the surface material and operation of the thrusters.

A plasma diagnostics package (PDP) was flown on space shuttle during the STS-3 mission and the results were summarized by Papadopoulos (ref. 3) as follows:

"Simply attempting to establish the spectral character of the emission, while ignoring the character of the associated plasma environment, might produce a very ambiguous and subjective interpretation, which by no means can be used to evaluate the impact of the spacecraft-related contamination to future shuttle payloads or to space platforms and telescopes. The following summary of the plasma environment measured by the PDP convincingly indicates that collective plasma processes play a large role in the proper evaluation of the orbiter contamination:

> (I) The plasma density (n) in the vicinity of the orbiter was often found several times and up to an order of magnitude higher than the ambient plasma density (n_0). It is like an ionized cloud surrounding selective areas of the spacecraft;

(II) Energetic (20-100eV) electron fluxes up to $10^{14}el/cm^2sec$ were measured, with the maximum occurring during daytime conditions;

(III) Ion fluxes with energies of up to 30eV were observed, sometimes coincident with single or counter-streaming ion beams with 10eV mean energy;

(IV) In addition to O^+, NO^+ and O^+2, H_2O^+ was observed, being on occasion the dominant species;

(V) An intense electrostatic broadband noise between low and high frequency cutoffs at 30 Hz and 20kHz, respectively, was measured, with amplitude to 1 v/m;

(VI) A gas layer of up to 10^{-5} torr was associated with surfaces ramming into atmospheric gases. Large pressure increases were observed during thruster operations and with payload bay doors closed;

(VII) Most of the plasma as well as glow phenomena were intensified during daytime RAM conditions and during thruster operations."

According to this summary, a spacecraft in low earth orbit is like an artificial comet and its glow is the coma.

The Effect on Passive and Active Operation of Antennas

The power spectrum of the plasma discharge is not well established. The measurements of the glow discharge with PDP indicated that the power density in the red and infrared wavelength are the predominant radiations in the higher frequency spectrum (ref. 4). The space shuttle glow density was measured photographically and amounted to a few hundred Rayleighs per Angstrom with a spectrum increasing toward the infrared (ref. 5). It was reported that the lens system for the very high resolution radiometer (VHRR) lost its transmissivity by 30-40% per mission because of glow discharge with atomic oxygen and sun radiation effects (ref. 6).

During skylab missions, the S193 microwave radiometer-altimeter/scatterometer and the S194 L-band radiometer antennas showed discoloration due to plasma contamination (ref. 7). The antenna pitch and yaw control also experienced difficulties due to contamination from the discharge transfer of aluminized mylar from the antenna.

At the low frequency end of the spectrum, the investigation of broadband electrostatic noise in the magnetotail of the mangetosphere (see fig. 2) in relation to plasma sheet dynamics revealed spectral densities of 10^{-5} to 10^{-16} V^2/m^2Hz from 1 Hz to 100 KHz respectively which could generate serious interference to low frequency radiometers (ref. 8).

A detailed description of the origin of the low frequency energies is given in ref. 9. The author mentioned the ion-cyclotron dynamics with its VLF signals and the plasma waves with the frequencies up to 300 KHz as the main electrostatic interference. The propogation mode of these waves is mostly in the form of whistlers. Also mentioned are hybrids of the different waves which contribute to higher frequency interference. The result of many investigations (ref. 9) from satellites is compiled in fig. 2 which shows the regions of plasma wave occurrence located in a noon-midnight meridional cross section of the magnetosphere. It is obvious that a low earth orbiting satellite encounters only the plasma sphere when its orbit is close to the equator. A polar orbiting satellite however, has to cross through many different vastly varying electrodynamic environments and can experience dramatic interferences.

A NASA conference in October, 1983 was dedicated to spacecraft environmental interactions which addressed problems of collecting negative surface potentials of spacecrafts from the plasma in low earth orbits (ref. 10). Many authors pointed out that discharges from surfaces covered with KAPTON would induce corona discharges in antenna feeds of passive systems and strong arcing in antenna feeds of active systems such as radars and communication systems with medium and high power outputs. Examples of this problem are given in ref. 11, where it is emphasized that the coupling effect between plasma current and the accumulated potentials at the feed point impedance is an important factor in spacecraft discharge electromagnetic interference.

The Glow Discharge and Temperature Variation Effects on the Material of the Mesh and Cords of the Hoop-Column Antenna.

One of the large space-structures of particular interest is the 15-meter Hoop-Column Antenna which is shown fully deployed in fig. 3. The column and the extended hoop keep the reflecting mesh membrane in the shape of parabolic reflector. The tension cords can be controlled by motors to readjust the surface if necessary. The feed systems are located over the parabolic reflector to function in a selected mode of a single or multi-beam system. The mesh material is knitted, goldplated molybdenum or tungsten wire in a tricot pattern as shown in fig. 4. The wire has a 30μ m diameter. The gold plating is 0.25μ m or 250 A° thick. The mesh may have different loop openings per diagonal unit length. The higher the density of loops, the higher the reflectivity and the higher the useable operating frequency. It is important that the wire loops are pretensioned and make good physical contact. These wire contacts play an important role in antennas used for passive applications such as radiometry. If the contacts represent lossy junctions instead of short connections a radiometer measurement will be in error by the random noise power generated in the connection losses.

How the atomic oxygen in an energized level of a plasma discharge may affect the electromagnetic and mechanical properties of large deployable structures such as the Hoop-Column Antenna will be addressed in the following section.

As explained in section "The Characteristic of Space Glow Discharge" the atomic oxygen is the most chemically active specimen in low earth orbit. So far, investigations have been conducted on board the space shuttle during STS-3, STS-4, STS-5, and STS-8 on KAPTON, MYLAR, TEFLON, TEDLAR and POLYTHYLENE to determine the oxidation process in the presence of charged particle plasmas. At an oxygen fluence between 0.65 and 3×10^{20} Atoms/cm^2 (depending on altitude) material thickness losses between 0.5 μm and 13 have been measured for an average orbit exposure time of 40 hours which represents a reaction efficiency of 0.5 to 4×10^{-24} cm^3/Atom (ref. 1). Any small losses within the mesh contact points contribute to measurement errors of brightness temperatures received by a radiometer, especially if the temperature of the mesh also changes. Very drastic temperature changes have been experienced in space on the surface of satellites and skylab (app. 250°K) (ref. 6). According to available literature, the effect of atomic oxygen on the contact points of goldplated wires with molybdenum, tungsten or other base metals has not yet been investigated.

In order to obtain a first order approximation of metallic changes which take place under similar circumstances, the related work by several investigators will be discussed and related to space environment. These investigators (ref 12) tested the reliability of packaging micro-electronic devices consisting of gold-plated Kovar, an iron, nickel and cobalt alloy. For that purpose, a base metal (iron, nickel or cobalt) was deposited by evaporation on a quarz substrate in a vacuum deposition system. A gold layer of 3000A° thickness was evaporated over the base metal. After heating the bilayer film to 229°C for hours at atmospheric condition, a strong spectrum component of Fe(2p) and O(1s) was measured with an x-ray photoelectron spectroscope. An example is given in fig. 5. Fig. 5 a) shows the spectrum before and fig. 5 b) after the heating to 229°C. This indicates a diffusion of iron molecules through the gold lattice by the chemical forces of the molecular oxygen. After penetration, the iron is oxydized. Nickel and cobalt show lesser diffusion rates than iron. In order to show that oxygen is the active element, the bilayer gold-iron was heated in a vacuum chamber under a N_2 or H_e environment. No surface accumulation of the base metal was observed. This indicates that molecular oxygen in the atmosphere at the earth surface is already chemically active enough to force the underlaying molecules through the lattice structure of the gold and oxydize it on the surface. A similar effect was discovered by the manufacturer of a mesh membrane antenna. The microwave losses (15 GHz) of the mesh increased two and three fold after a long time exposure of the antenna in a stowed position under atmospheric condition, i.e., the contact points of the tricot pattern were not under tension. In order to remove the contact point losses of the oxydized base material, a burnishing procedure was necessary to restore the reflector surface to theoriginal reflectivity (Boan, B. J., Private Communication, July 26, 1984).

From these experiences, one could assume that the diffusion of the base metal through the gold plated lattice and its subsequent oxidation would be accellerated if the mesh of a large space antenna were exposed to low earth orbit environment because of the following conditions:

a) temperature cycling and/or gradients (300K) along the antenna surface are generated by alternating sun and shadow side along the orbit.

b) atomic oxygen (more active than molecular) is the main constituent of the low earth orbit.

c) the plasma discharge increases the impact velocity of the oxygen at the surface.

In order to understand the effects to be expected in a space environment, the properties of a gold-molybdenum oxide-gold (Au-MoO_3-Au) junction is described which was produced in the laboratory and extensively tested (ref. 13). Fig. 6 shows the Au-MoO_3-Au junction as it was produced in a vacuum chamber with an electron beam evaporation process. As pointed out in ref. 14, the majority of investigators of metal-insulator-metal junctions consider it a well-accepted fact that the interfaces between the metal and the insulator represent a doped semiconductor interface and interpret these interfaces as Schottky-barriers. Fig. 7a shows the diagram of the proposed energy bands for the metal-doped-insulator-metal junction. The depletion layer is λ_0 thick and the entire junction has the dimension S. Because of the doping in the Schottky barriers, the junction is highly temperature dependent. An equivalent circuit diagram is shown in fig. 7b. The capacitances C_s are the Schottky barrier capacitances and C_b the interior capacitance which has in parallel a temperature dependent resistance R_b. The value of R_b is also dependent on the number of electrons exited from donor centers and can be expressed as

$$R_b = R_o \; e^{\phi/2kT} \qquad (1)$$

where ϕ is the ionization energy of the donor centers, K is Bolzmann's constant, T is the temperature in Kelvin and R_0 is the basic resistance of MoO_3. The impedance of the circuit of fig. 7b) is

$$Z = \frac{1}{1 + j\omega C_b \ R_o \ e^{\ \Phi/2kT}} + \frac{2}{j\omega C_s} \tag{2}$$

The impedance Z can be separated into a real part and a capacitive part (R+jWC). The investigators of ref. 14 showed in fig. 8 how strongly C depended on the temperature T. The relative large capacity C is the result of the large area ($203mm^2$) of MoO_3 and the small thickness ($0.5\mu m$) of MoO_3. The measured relative dielectric constant of MoO_3 is $\varepsilon = 15.8$.

From the results of this experiment, it may be stated that the contact points of a mesh wire loop of a mesh membrane antenna will be affected by the atomic oxygen - plasma discharge and possibly create a Au-MoO_3-Au Schottky barrier junction which has been found to be extremely temperature sensitive, with capacitance changes of 50:1 possible over a 100°K temperature range.

An additional effect caused by the atomic oxygen-plasma discharge is concerned with the property changes of carbon-fiber cords such as those used to keep the tension on the parabolic mesh reflector, shown in fig. 3. As mentioned in ref. 14, carbon filled materials may react at rates similar to organic materials. First investigations indicated a reaction efficiency of $0.9\text{-}1.7 \times 10^{-24}\ cm^3$/Atom. For example, Kevlar fiber used instead of carbon-fiber Hoop Column cords could experience a strength reduction of 30 percent or larger over a 40-hour exposure time.

Concluding Remarks

As described in the previous sections, the plasma discharge in low earth orbits of spacecrafts is not negligible, as is the case for high orbits such as the geostationary orbit of communication satellites. The plasma discharge effect is at its maximum in the area close to the poles of the earth axis. Special attention has to be directed to the instruments and materials exposed to the plasma environment around the space shuttle or satellites in low earth orbit. Of particular interest is the utilization of a mesh membrane large space antenna such as the hoop column antenna. Additional studies and research are needed which address the effects:

a) of microwave noise generation which could degrade the measurement results of brightness temperature in the field of radio astronomy and passive remote sensing of the earth surface.

b) of the structural changes of deployed reflector mesh.

c) of reduction of the breaking strength of the carbon-fiber cords of deployed surfaces.

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TABLE 1. AMBIENT ATMOSPHERE CONCENTRATION (NOMINAL) (CM^{-3})

SPECIES	ALTITUDE (KM) 200	300	800	EQUIVALENT KINETIC ENERGIES EV
N_2	$2{\cdot}6\times10^9$	$1{\cdot}06\times10^8$	$1{\cdot}01\times10^2$	9.3
O_2	$2{\cdot}97\times10^9$	$7{\cdot}66\times10^6$	1·01	10.6
O	$3{\cdot}18\times10^9$	$4{\cdot}72\times10^8$	$1{\cdot}7\times10^5$	5.3
Ar	$3{\cdot}14\times10^6$	$3{\cdot}31\times10^4$	$8{\cdot}39\times10^{-5}$	14.7
He	5.16×10^6	3.11×10^6	$4{\cdot}28\times10^5$	1.3
H	1.92×10^5	1.63×10^5	9.88×10^4	.3
NO^+	3×10^5	1.5×10^4	-------	
O_2^+	8×10^4	6×10^3	-------	
O^+	8×10^4	5×10^5	-------	

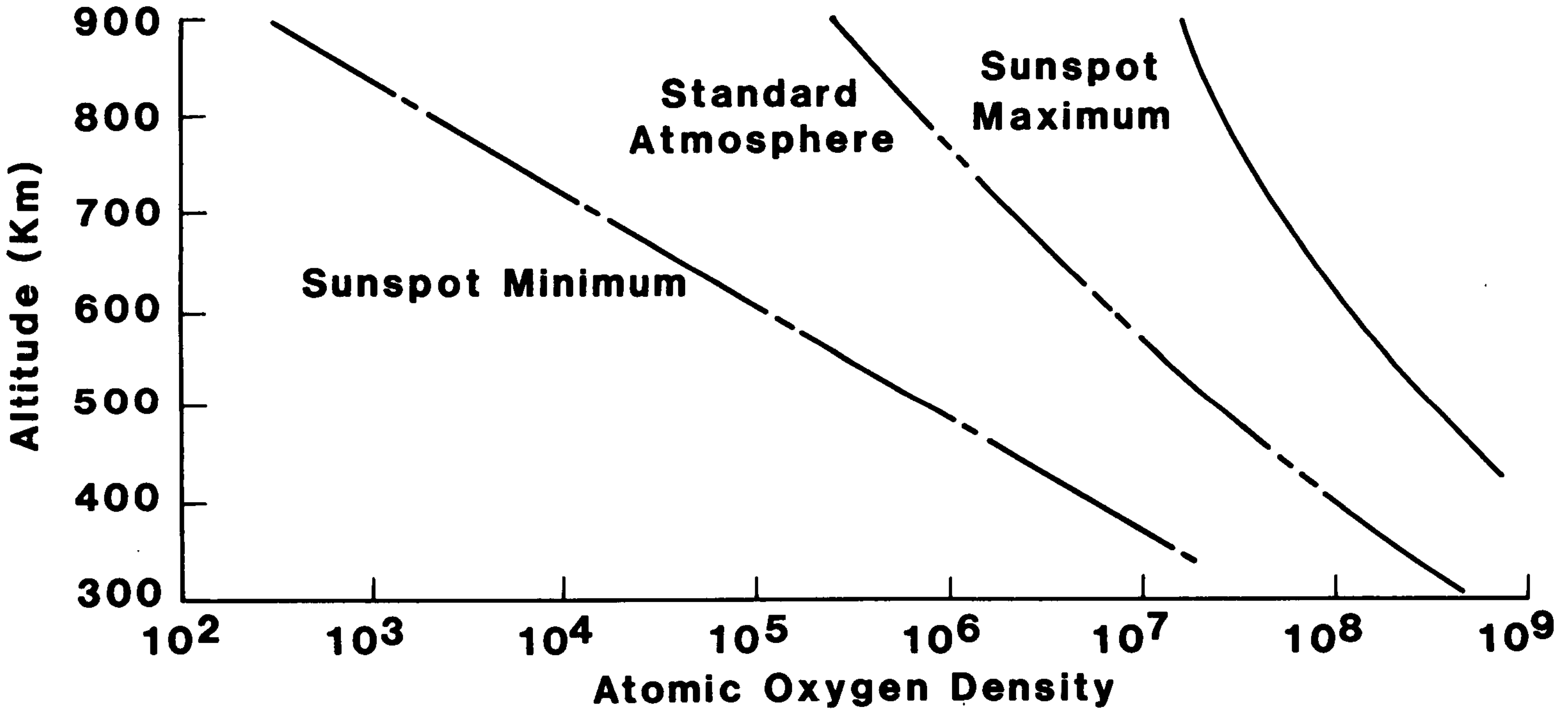

FIG. 1. Atomic Oxygen Density Versus Altitude

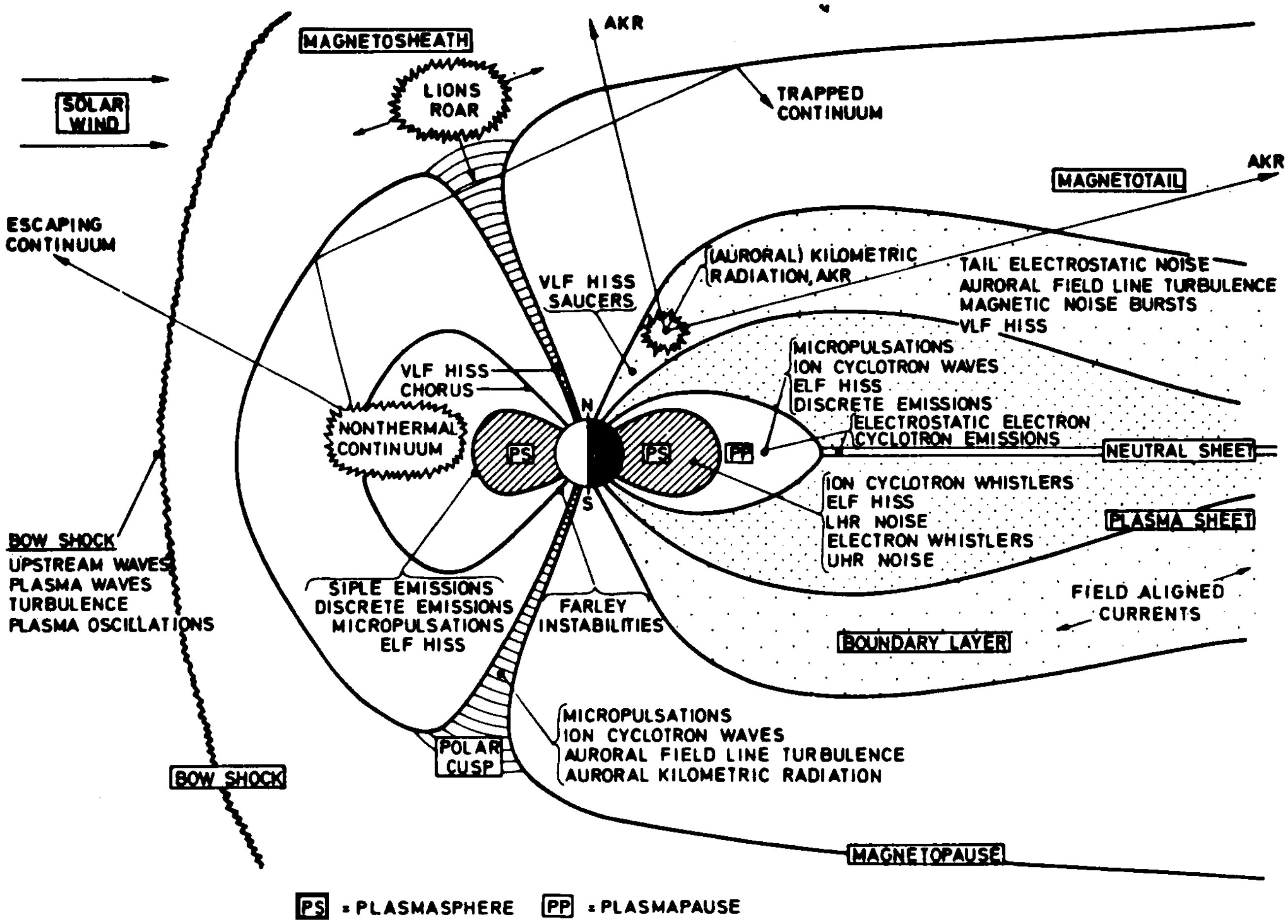

Fig. 2. Regions of plasma wave occurrence located in a noon-midnight meridional cross section of the magnetosphere. (ref. 8)

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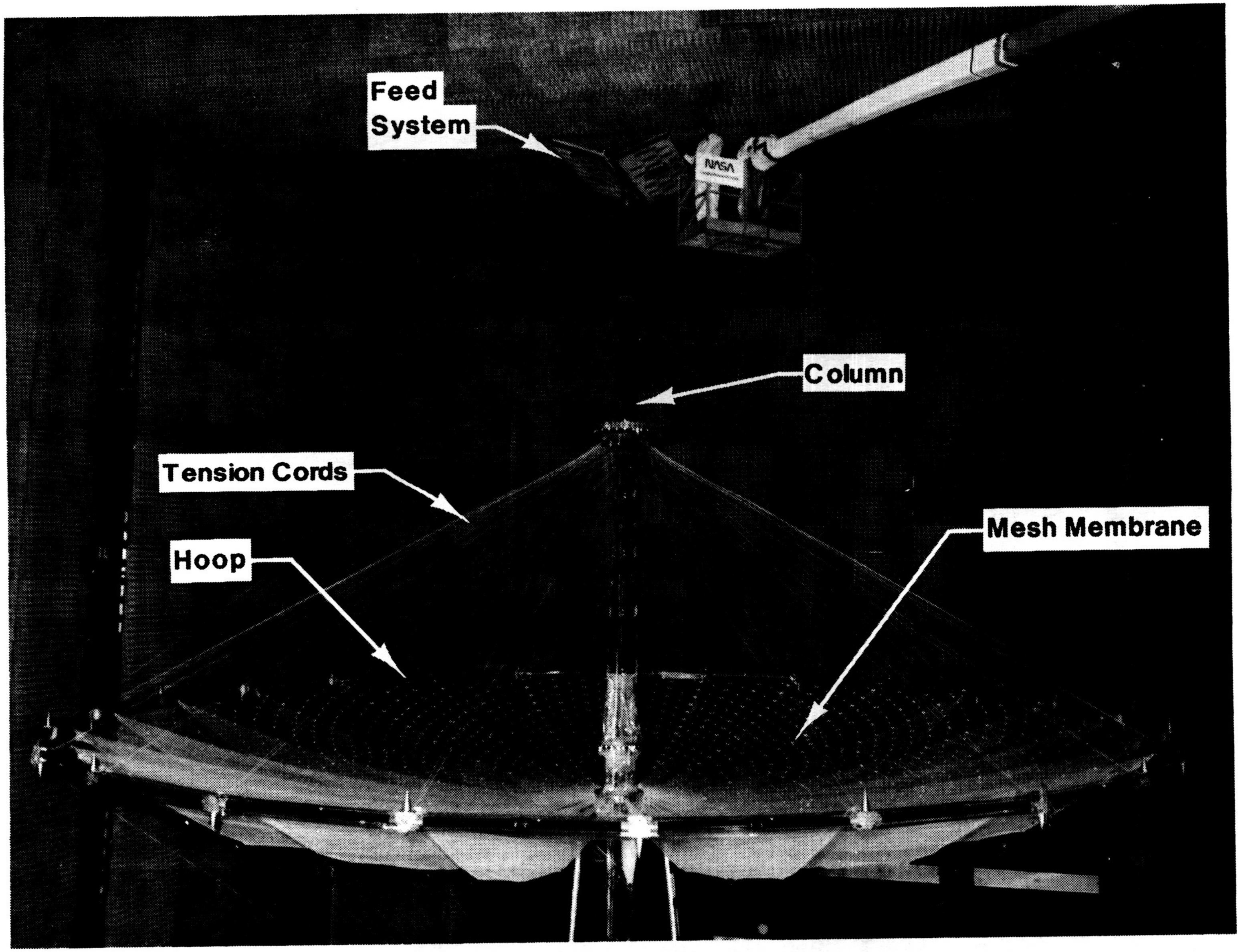


Fig. 3. Deployed Hoop-Column with Mesh Membrane as the Parabolic Reflector.

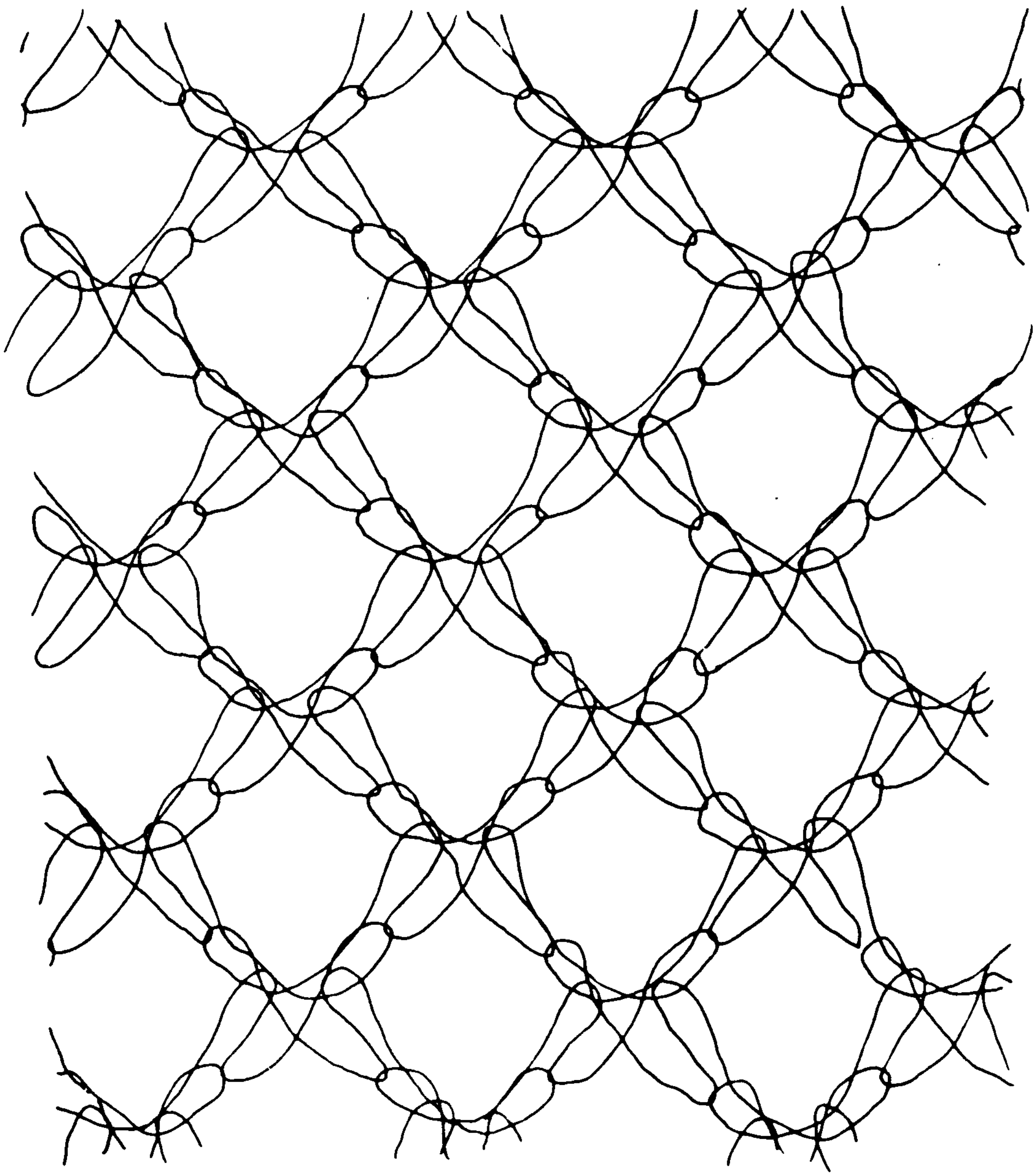
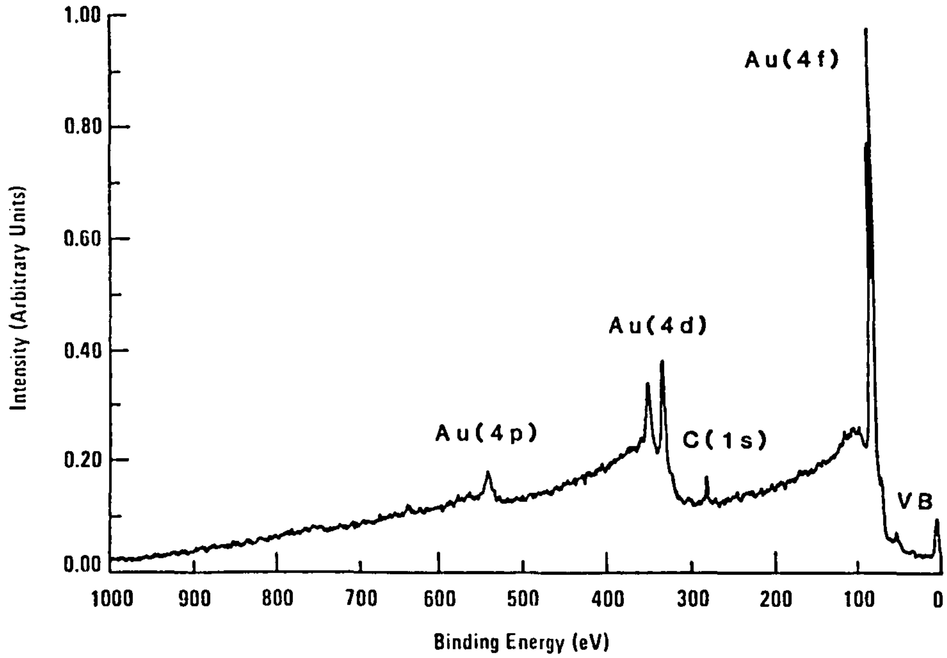
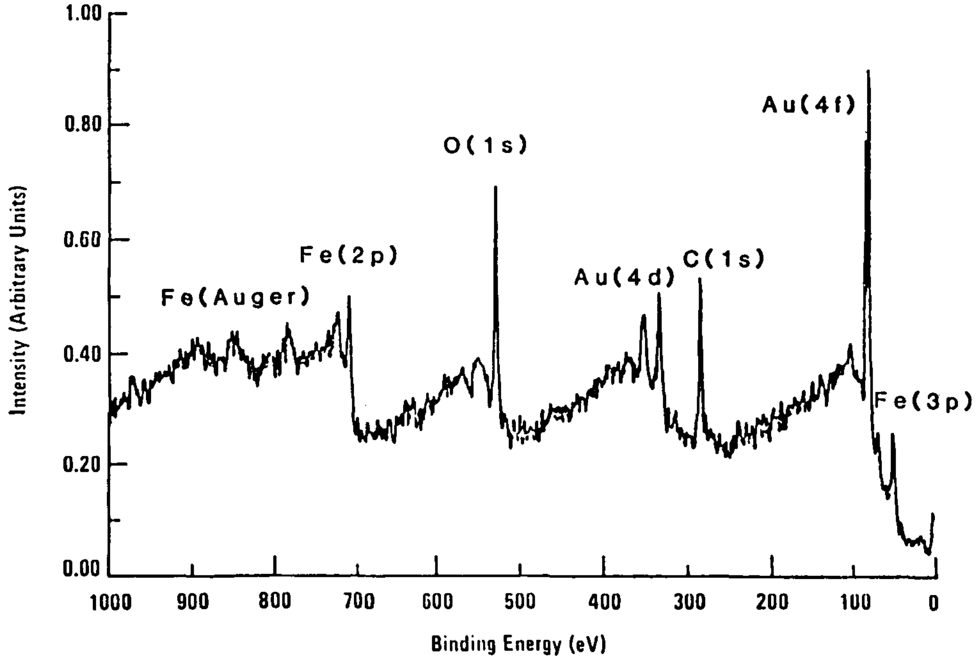


Fig. 4. Gold plated Molybdenum Wire Knitted into a Tricot Pattern



a) XPS Survey spectrum of an unheated Au/Fe bilayer film.



b) XPS Survey spectrum of an Au/Fe bilayer film heated to 229°C for 1.5h.

Fig. 5. X-ray Photoelectron Spectroscope of the Gold-Iron Film on a Quarz Substrate

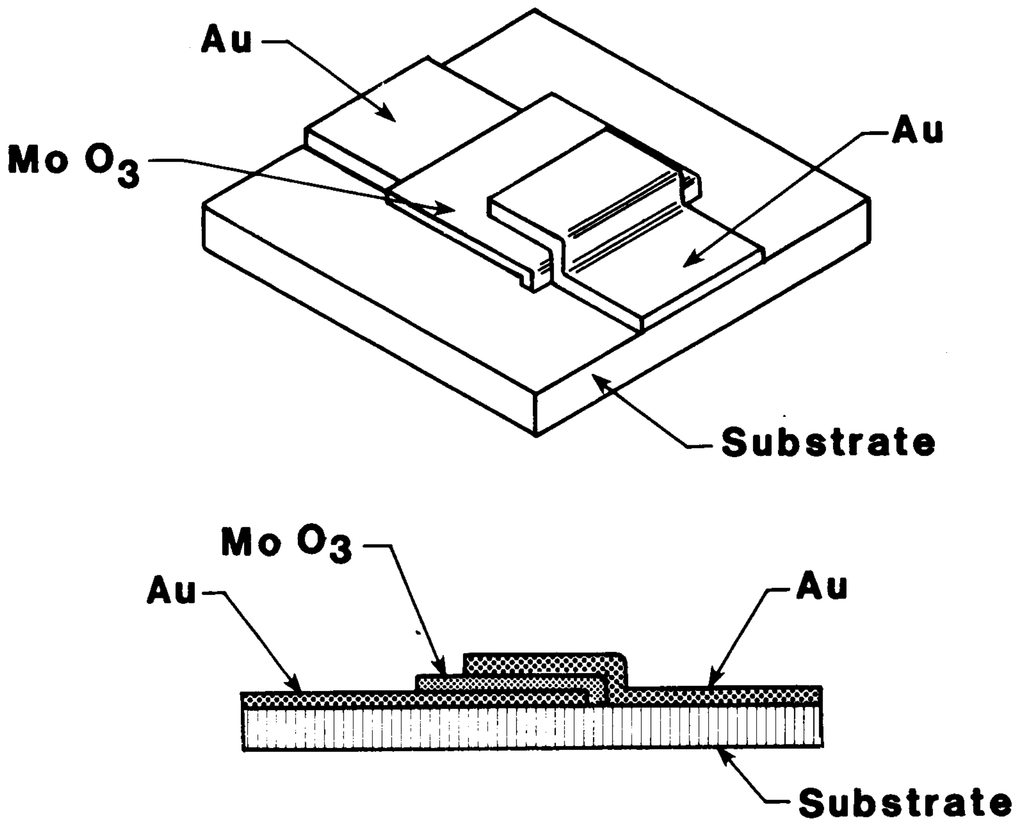


Fig. 6. Gold-Molybdenum Oxide - Gold Junction

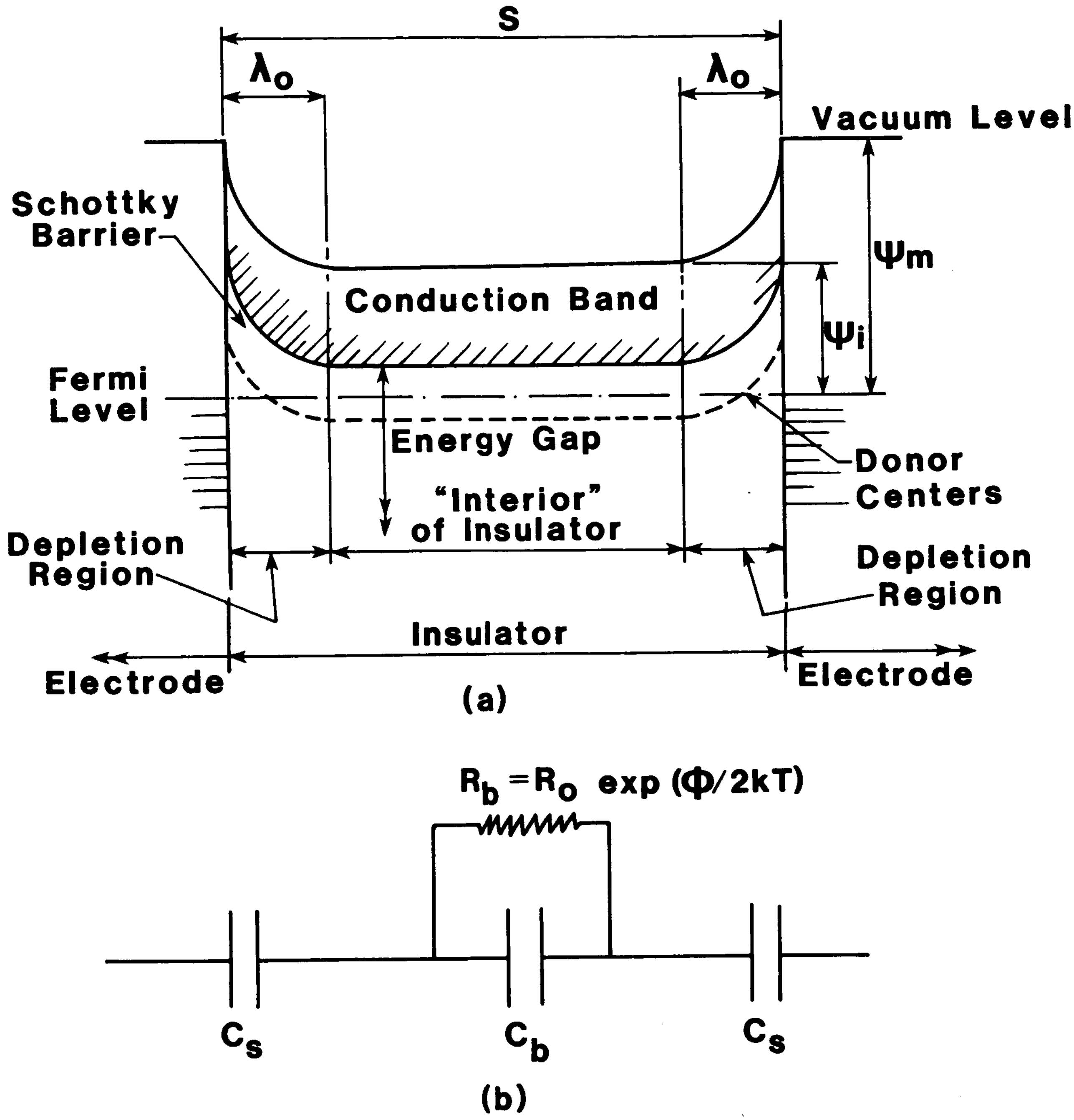


Fig. 7. Diagrams of (a) proposed energy band diagram for metal-(doped) insulator-metal system, and (b) equivalent circuit for system shown in (a).

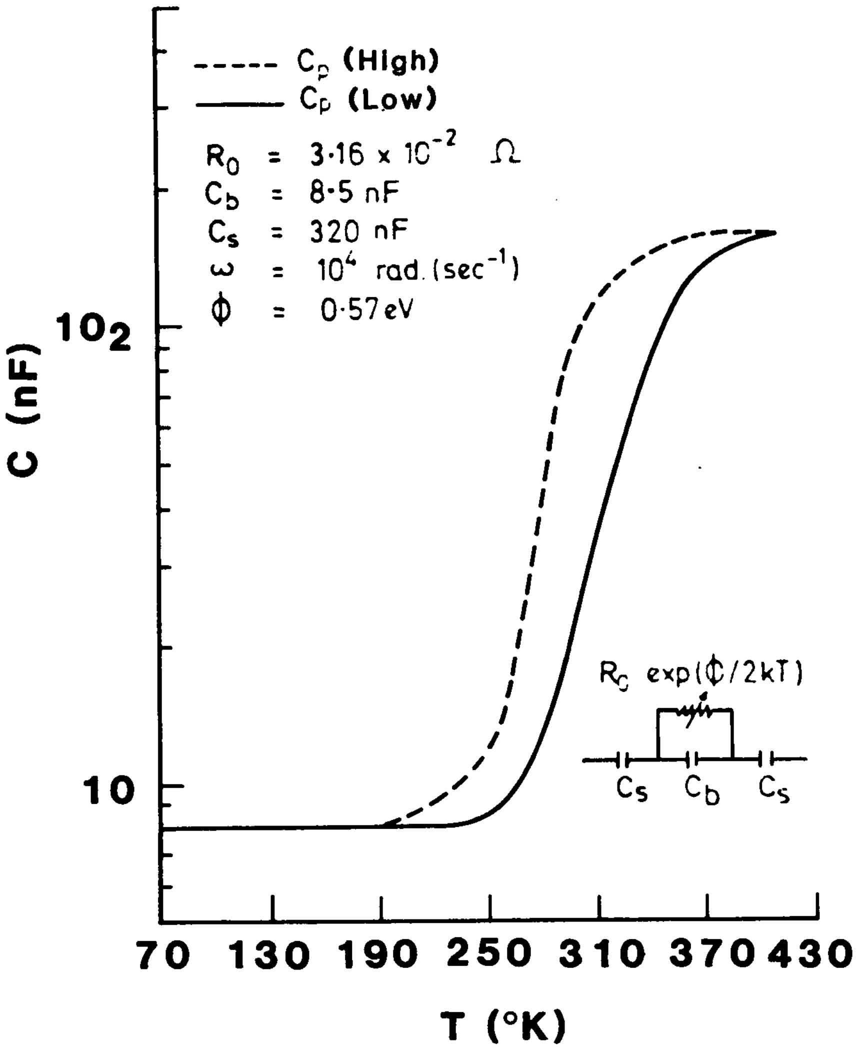


Fig. 8. Theoretical C-T diagram calculated using equation (2) of the text.

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15. Supplementary Notes

16. Abstract

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