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DIAMOND-LIKE ANTIREFLECTIVE COATINGS FOR FAR INFRARED PHOTOCONDUCTORS

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Résumé – Des films de type diamant ont été utilisé comme couche antireflet dans des semiconducteurs photoconducteur travaillant dans l'infrarouge lointain. Une augmentation moyenne de 28% a été observé dans la réponse du détecteur, pour des photoconducteurs à film de germanium dopé au gallium, cela comparé au détecteur sans film. Les photoconducteurs étaient réalisés à 3 K, sans cavité, dans une Êtroite région de longueur d'onde allant de 98.45 à 99.35 μm. Les films survivent bien à des cycles thermals répètés entre 2.5 K et la température ambiante. L'augmentation du courant résiduel causée par le dépos est $\leq 10^{-14}$ A, valeur obtenue par l'instrumentation. Les qualitiés protectices du film sont explorées. Les applications potentielles du film photoconducteurs de type diamant dans des ensembles larges avec ou sans tension, qui seront utilisés dans l'avenir, dans des expériences d'astrophysique à bord de sattelite, sont discutées.

Abstract – Diamond-like films have been used as antireflective coatings on far infrared semiconductor photoconductors. An average increase in the detector responsivity of 28% was realized for optimally coated gallium-doped germanium photoconductors compared to uncoated devices. The photoconductors were operated at 3 K without cavity in a narrow wavelength range from 98.45 to 99.35 μm. The films survived repeated thermal cycling between room temperature and 2.5 K. Any increase in dark current caused by the coating is $\leq 10^{-14}$ A, a value which is given by instrumentation. The protective qualities of the film are explored. The potential applications of diamond-like coated photoconductors in large, unstressed and stressed arrays which will be used in future, satellite-born astrophysics missions will be discussed.

The successful mission of the Infrared Astronomical Satellite (IRAS), a liquid helium cooled far infrared telescope which circled the earth for close to one year, provided the first survey of the infrared sky. The overwhelming number of new discoveries, including thousands of hitherto unknown glaxies, dust clouds emitting far infrared radiation, starbirths, *etc.*, has led to an intense research and development effort for future missions. Key elements for such telescopes are the infrared detectors. They consist of small parallelpipeds of impurity-doped semiconductors. Depending on the particular IR band, a specific combination of semiconductor and dopant impurity is chosen. Typical combinations are; silicon doped with indium (Si:In) for 1.3 to 7 μm, silicon doped with arsenic (Si:As) for 17 to 21 μm, germanium doped with beryllium (Ge:Be) for 30 to 50 μm, and germanium doped with gallium (Ge:Ga) for 60 to 120 μm. If uniaxial stress is applied to Ge:Ga detectors, the long wavelength limit can be extended to approximately 250 μm.

Impurity doped semiconductor photoconductors, also called extrinsic photoconductors, operate as follows /2,3,4/, taking the case of Si:As, for an example. Each arsenic impurity occupies a silicon site. Arsenic has five valence electrons, one in excess of what is needed to bond to the four silicon neighbors. The fifth electron is bound to the arsenic impurity with 49 meV, an energy so small that at room temperature the electron is lifted into the conduction band where it is free to move, making the silicon crystal n-type (electron) conducting. Upon cooling the crystal to a very low temperature, the dopant-generated electrons "drop" back into the impurity energy state, *i.e.*, the electron is bound to the arsenic. The crystal loses its conductivity, and becomes highly resistive. When infrared photons with an energy > 49 meV impinge on the cold Si:As device, arsenic-bound electrons are lifted into the conduction band through photon absorption. During the time the photons are residing in the conduction band (called "lifetime"),

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the electron can move freely. this phenomenon is called "photoconductivity," and it represents the IR photon detection mechanism.

To maximize infrared detector performance, we need to balance many parameters. As indicated above, gallium-doped germanium detectors are currently used for detecting signals in the 100 micron wavelength region. The characteristic absorption length of photons of this wavelength is 5 mm in the detector. Therefore, to make use of all the available photons, we need detectors with an "absorption length" of at least 5 mm. Unfortunately, using detectors with such large dimensions increases their sensitivity to cosmic ray disturbances. Infrared detectors are operated at high altitudes in balloon- or airplane- borne instruments, or they are launched into orbit in satellites; they must be used above the infrared-absorbing atmosphere in order to be reached by the IR photons. However, at these altitudes the semiconductor devices are more susceptible to cosmic ray interference coming from outer space. Cosmic ray "hits" produce very large signals, and also disturb a detector's responsivity for long periods of time. Obviously, the larger the detector, the greater its chances of being hit.

Another concern of astronomers is being able to image the shape of infrared sources in space. Arrays of closely-packed detectors are mounted in the focal planes of specially designed telescopes. Each detector in the plane constitutes a pixel on the final image. To achieve the highest resolution possible, we need to make the detectors increasingly smaller and pack them as closely together as possible.

Taking into account these constraints, a recent study /5/ proposes an optimized detector geometry as shown in Fig. 1. Light enters the chip via a 0.5×0.5 mm^2 incident surface, and is internally reflected a number of times within the detector length. However, one problem encountered with this type of detector is the relatively high signal loss due to incident surface reflection.

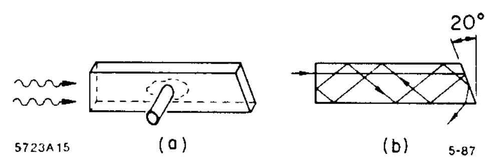

Fig. 1. – An end-fire detector (a) perspective view of $2.5 \times 0.5 \times 0.5$ mm detector. (b) An optical path through an end-fire detector.

Semiconductors have high dielectric constants, and as a result, high indices of refraction. For germanium infrared detectors, this translates into a 36% loss of incident signal. To recover this loss, an antireflection coating is needed.

To produce such a coating, we need a material with an index of refraction n_{arc} corresponding ideally to the geometric mean of the indices of refraction of vacuum 1 and of germanium 4. The thickness d of the antireflection coating at wavelength has to be

$$d = \frac{\lambda}{4} \times \frac{m}{n_{arc}}$$

where m is an integer. The coating for use on detectors must also be a good insulator or we would create a path for a parasitic "leakage" current across the device. Diamond-like carbon, DLC, layers have recently been produced with indices of refraction approximately equal to two, which is close to ideal for germanium and silicon detectors and with resistivity as high as 10^{12} Ω cm. Various deposition techniques have been reported for deposition of DLC which involve film growth under ion bombardment. The RF technique developed by Holland /6/ is widely used due to its high current densities (*i.e.*, high deposition rate) and uniform film growth over large area as compared to ion beam techniques. However, DLC coatings can spontaneously break up or the adhesion to substrate may fail as shown in Fig. 2 when their thickness reaches the micrometer region /7/ presumably due to internal stress produced by absorbed hydrogen. We have developed a new technique /8/ in which ion flux and ion energy are controlled by two separate RF fields. DLC films produced in this system are relatively strain free and can be grown in layers thick enough (12.5 μm) for this application.

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Fig. 2. – Relief of compressive stress after detachment from base causes wrinkling of thick DLC film.

I – EXPERIMENTAL

i. A 0.5 mm wafer of gallium-doped germanium (concentration of Ga $\simeq 2 \times 10^{14}$ cm^{-3} was cut, polished, implanted with B^+ ions (for the formation of ohmic contacts), metallized and annealed as described elsewhere (See reference 9). From this wafer, detectors were cut 0.53 mm wide, and 2.53 mm average length. An angled back surface was cut at 20° off axis compared with the front surface. Etching for 15 seconds in a 4:1 HNO_3:HF solution polished the germanium surfaces, and reduced the final dimensions to 0.5 × 0.5 × 2.5 (average) millimeters. Each detector was then tightly wrapped in pure indium foil, leaving the incident surfaces exposed. A copper plate was prepared 0.25 inches thick, with 0.125 inch holes drilled through it. The indium-wrapped detectors were pressed into the holes far enough so that the exposed incident surfaces were nearly flush with the surrounding surface of the copper plate. Enough indium foil was used so that this resulted in a tight press fit and good heat conduction.

ii. Coating System: The deposition apparatus is fully described in ref. (8). Briefly, it consists of a pyrex cylinder 15 cm diameter × 30 cm high evacuated through a throttling gate valve by a diffusion pump, which can achieve a base pressure of 1×10^{-7} Torr. High purity CH_4 (99.99%) is leaked into the system via the upper electrode, which is a Pyrex beaker of 6 cm inside diameter, surrounded by an RF coil powered by a 2 MHz RF generator, forming an RF oven. Hydrocarbon gas is dissociated and ionized within the beaker and ionization is further enhanced by an axial magnetic field which contains the plasma in the cylindrical volume between the two RF electrodes.

The lower electrode which is the work holder is a water cooled, planar copper, 6 cm diameter disc coupled to an RF generator via a power meter and an impedance matching π–network. The temperature of the growing film is measured by a pyrometer focused at the surface of the substrate. The plasma intensity and the negative dc self bias of the substrate can be controlled by changing the power to the RF oven and the power to the lower electrode (substrate holder). The plasma is almost completely confined by a magnetic field to the volume between the two electrodes at the center of the chamber. The deposition parameters are: 10^{-2} Torr. CH_4, oven power ≈ 30 W, workholder electrode power 100 W, reflected power < 5%, bias voltage 450 V, and deposition rate of 8.6 nm min^{-1}.

II –RESULTS AND DISCUSSIONS

One of the finished devices was mounted and tested in the apparatus shown in Fig. 3. To limit the amount of "background radiation" coming from its surroundings, the device is mounted in a light-tight box coated with black IR absorbing paint. At the front of the box was one small source hole for photons. The incoming signal is narrow band filtered and attenuated to produce a signal comparable in intensity to those experienced in space. The strength of the infrared signal (expressed in watts) can be calculated knowing the temperature of the photon source, and the throughput of the various filters. The voltage (or bias) applied across the detector is an additional variable.

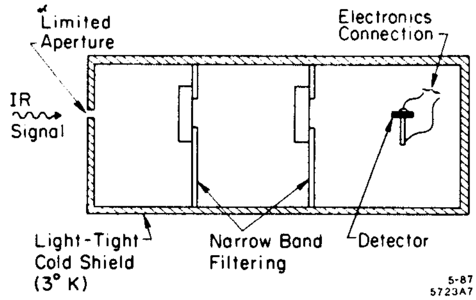

Fig. 3. – Infrared detector test apparatus.

The detector characteristics of most interest are the responsivity, and the Noise Equivalent Power (NEP), which is a measure of the signal-to-noise ratio. The responsivity is the ratio of the current passed through the detector as a function of the incident signal power, measured in amps per watt. As seen in Fig. 4, the diamond-coated detector achieves an average of 28% higher responsivity, compared to an uncoated reference detector.

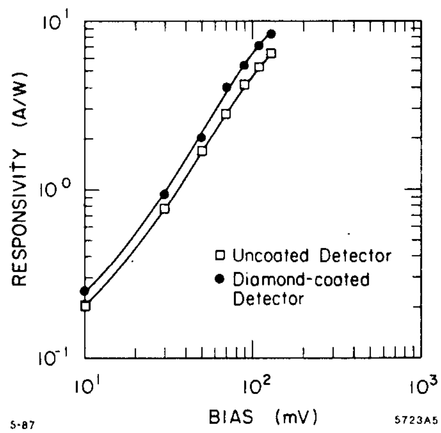

Fig. 4. – Responsivity as a function of bias for both DLC coated and uncoated detectors. An average increase in responsivity of 28% was attained using DLC antireflective coating.

The NEP is defined as the amount of incident power required to give a signal-to-noise ratio of one. Fig. 5 demonstrates the improved NEP as a function of bias for the coated detector.

A third parameter of interest is the dark (leakage) current. The dark current should be reduced as much as possible because it causes signal fluctuations which can obscure weak IR signals. To determine the leakage, the incident photon flux is blocked entirely, and the dark current flowing through the device is measured. For the two detectors tested, leakage currents were essentially the same (within the error bars of our test apparatus which is approximately 10^{-14} A. When operating the devices at half their breakdown voltage (60 meV across a 0.5 mm interelectrode distance, or 1.2 V/cm), leakage currents were no greater than 3×10^{-14} A.

From these tests we conclude that the diamond-like carbon layer deposited on the incident surface of our detectors enhanced their 100 μ light absorption without increasing the measured noise and dark current. However, some new telescope designs demand detector dark currents of less than 500 electrons per second (8×10^{-17} A). Further tests need to be performed under lower background conditions and with special current integrating amplifiers to determine whether the

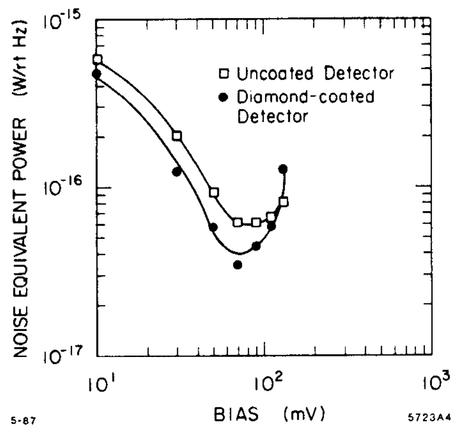

Fig. 5. – Noise as a function of bias. The detector with the DLC coating on the incident surface showed no appreciable increase in noise throughout its operation.

coated detectors can meet these low leakage current requirements. In summary, we can state that diamond-like antireflection coatings fulfill the optical as well as electrical requirements posed by far IR detectors for low photon background applications ($< 10^8$ photons/second). This opens up the possibility of making large multidetector arrays that operate at the diffraction limit, and which use multiple reflections within the individual devices. To date, we have demonstrated the usefulness of the coatings for far IR Ge:Ga photoconductors only, but we expect that the coatings would perform as well on other Ge and Si detectors. Films as thick as 12.5 μm have been repeatedly cycled between room temperature and 2.5 K and show no deterioration. Additional benefits may be found in surface passivation and protection.

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