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A STRESSED PHOTOCONDUCTIVE DETECTOR FOR
FAR-INFRARED SPACE APPLICATIONS

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Abstract

An optimized leaf-spring apparatus for applying uniaxial stress to a Ge:Ga far infrared photoconductor has been designed and tested. This design has significant advantages for space applications which require high quantum efficiency and stable operation over long periods of time. The important features include adequate spring deflection with relatively small overall size, torque free stress, easy measurement of applied stress and a detector configuration with high responsivity. One-dimensional arrays of stressed photoconductors can be constructed using this design. A peak responsivity of 38 A/W is achieved in a detector with a cutoff wavelength of 200 μm which was operated at a temperature of 2.0K and a bias voltage equal to one half of the breakdown voltage.

I. Introduction

The need for sensitive detection of far-infrared photons from astronomical sources can be well satisfied by extrinsic photoconductive detectors for wavelengths up to $200\mu\text{m}$.

Photoconductors made from Ge:Be are used¹ when optimized far infrared measurements are made in the wavelength range from $30\text{--}45\mu\text{m}$. Unstressed Ge:Ga covers² the region from $45\text{--}110\mu\text{m}$. Extension of the long wavelength limit can be achieved by applying an uniaxial stress along a (100) axis of Ge:Ga.² The effect of this stress is to split the degeneracy of the valence band and to reduce the ionization energy of the Ga impurity states. The resulting shift of the onset of photoconductivity to longer wavelengths begins to saturate³ at about 66 kg/mm^2 giving a long wavelength cutoff of $220\mu\text{m}$. Stressed Ge:Ga photoconductors have been successfully used in far infrared astronomical observations from an airborne telescope^{4,5} and also in a photometric measurement of the diffuse sky brightness from a sounding rocket.⁶

It has been proposed to use arrays of stressed Ge:Ga photoconductors in space astronomy experiments such as those planned for the Space Infrared Telescope Facility⁷ (SIRTF) of the National Aeronautics and Space Administration and the Infrared Space Observatory⁸ (ISO) of the European Space Agency. The focal planes of the telescopes in such projects will be assembled more than a year before launch. Years of operating time are required. There are concerns regarding the stability of existing designs of

stressed photoconductors. Relaxation of the stress over time and repeated thermal cycles has been observed which has not been important for short-term projects, but could pose serious problems for space applications. This mechanical relaxation of the stress arises mostly from slow plastic deformation of the pads used to insure a uniform stress distribution over the detector. The first system developed for applying stress to an infrared detector² used a screw and a ball bearing to drive a piston in a very stiff yoke. A small amount of thermal contraction or plastic deformation therefore caused significant changes in the stress.

The problem of stress relaxation could be solved by avoiding stress distribution pads and using only elastic materials,¹⁰ but with either a degradation of stress uniformity or a significant tightening of mechanical tolerances. Good stability has been recently reported for a detector with a moderate value of stress designed for space applications.⁹ Although little information about stress distribution is given, the onset of photoconductivity is fairly broad, suggesting some inhomogeneity of the stress. The stability problem can also be solved by recent approaches which use a coil spring¹⁰ or a piezoelectric transducer¹¹ to provide the stress. The size and complexity of these approaches however limit their usefulness for space applications.

We have measured the compression of suitable stress distribution pads and established a criterion for the spring deflection required for long term detector stability. We have found that the required force and deflection can be obtained in an apparatus of relatively small size by using a stack of leaf

springs. In our design the stress is very uniform because adequate stress distribution pads are used and no torque is transmitted to the detector. Since the Young's modulus for the spring material depends only weakly on temperature and since the spring deflection chosen is large compared to the thermal contraction on cooling, the stress can be adjusted at room temperature in our apparatus. We show that the fractional change of detector resistance at the ice temperature is a useful measure of the applied stress and provide a calibration curve.

We have constructed several versions of the leaf-spring stress apparatus and have installed Ge:Ga detectors with the endfire geometry which we recently¹² showed to have good optical efficiency and high responsivity. Measurements of the absolute responsivity, spectral response and stability are presented. Finally, the modifications to the design required for linear arrays are described.

II. Design Consideration

In order to achieve stability in the applied stress the elastic deformation of the force transmitting medium has to be much larger than the plastic deformations which cause stress relaxation. As will be discussed below, we used an early version of our apparatus to show that stress distribution pads which give excellent stress uniformity can be made which relax less than 10 μ m over time and with repeated thermal cycles. Using such pads,

100 μm of elastic spring deflection is required to limit the shift of the cutoff wavelength for photoconductivity to 2% at high stress.

Since the peak stress in the spring must be less than the yield strength of the material, there exists an upper limit on its elastic deformation. When our criteria for force and deflection are met, designs involving columns under tension and compression, as used for the original stressed detector,² or the coil spring recently proposed¹⁰ have large overall size. We have chosen a more compact multiple leaf-spring design to provide the required force and deflection.

A scale drawing of our design is shown in Fig.1. The force is applied by turning a carbon steel #5-40 screw (a) which bends the stack of high-yield-strength spring steel leaf springs (b). The leaf-spring stack is supported in the center by a stainless steel saddle (c). The saddle slides into a groove in the stainless steel support (d) and is held by a steel pin (e). The force from the stack of springs is transmitted to the photoconductor sample (f) by the piston (g). Both the upper and lower pistons (g) are made of hardened drill rod which fit into reamed holes in the stainless steel support. The lower piston is supported by a carbon steel #4-40 screw (h). The leaf-spring assembly contains several springs with the same rectangular cross section, each of which supplies a fraction of the total force. The number of springs can be varied in proportion to the cross sectional area of the detector to be stressed. For example, four springs are used to stress a single $0.5 \times 1.0\text{-mm}^2$ detector as discussed below.

Our design is based on the conventional theory of the elastic bending of beams.¹³ Consider a stack of n springs made from material with Young's modulus E and yield strength Y . Each is assumed to have active length l , thickness t , width w , and is bent by deflection δ under the applied force F as illustrated in Fig.1. The equations which relate the force F to the deflection δ depend on the maximum allowed value of stress $T_{\max}$, which occurs midway between the ends of the springs. These equations can be conveniently written in the form

$$l = 3x^{1/3} \delta^{2/3} E^{2/3} / T_{\max}, \quad 1)$$

and

$$t = 3x^{2/3} \delta^{1/3} E^{1/3} / T_{\max}, \quad 2)$$

where

$$x = F/nw. \quad 3)$$

The design depends on the choice of spring materials through the ratios $E^{1/3}/Y$ and $E^{2/3}/Y$, which are not very sensitive to the materials chosen. We have successfully used a commercial spring steel with a safety factor $T_{\max} = Y/3$. A shortcoming of this material is the possibility of structural failure due to the transformation¹⁴ from an austenitic to a martensitic phase at low temperatures. During this phase transition shape deformations of the product phase occur. Large locally induced stresses result which may well exceed the yield strength of the material and

extensive defects can be introduced.¹⁴ The applied stress assists this phase transition.¹⁴ In the martensitic phase the material becomes brittle and is not suitable for use under stress at low temperatures. Series 400 stainless steels are in the martensitic phase at room temperature. Among series 300 stainless steels the 310 and 316 grades seem relatively safe to use. The problem of the phase transition can be avoided by the use of non-ferrous spring materials such as beryllium copper or titanium alloys. The properties of four possible spring materials are given in table I.

Some features of the stress apparatus depend sensitively on the geometry of the detector to be used. We have made a detailed optimization of the geometry of diffraction-limited far infrared photoconductive detectors which have infrared extinction lengths that are long compared with the pixel diameter.¹² A number of criteria were considered including absorption efficiency, electrode separation, volume and uniformity of illumination. The rod shaped geometry of the detector sample shown in Fig.2, which has square cross section, electrodes on the lateral faces, and a beveled backface to trap the radiation by total internal reflection, was found to give the best overall performance.

The transverse (pixel) dimensions of such detectors are limited by the throughput required for the focused diffraction-limited beam. For an $f/2$ focus, a stressed Ge:Ga detector with angular diameter λ/D used for wavelengths out to $200\mu\text{m}$ should have a pixel diameter of $\sim 0.5\text{mm}$. The optimum detector length is 0.3 to 0.5 times the infrared extinction length. This length in turn is determined by the concentration N_A

of Ga in the material and by the applied stress. This absorption length can be decreased by increasing N_A , but the detector dark current is expected to increase exponentially with N_A . Although the optimal impurity concentration of the stressed Ge:Ga photoconductor is still not precisely known, a guess can be made from the value $N_A = 2 \times 10^{14} \text{ cm}^{-3}$ for unstressed Ge:Ga detectors and theoretical considerations of impurity conduction.¹⁵ For use at high stress, the optimal doping is estimated¹² to be $N_A = 1 \times 10^{14} \text{ cm}^{-3}$. Our measurements of the peak optical extinction length¹² in this material for infrared photons propagating perpendicular to the direction of the stress is 2.5 mm at 55 cm^{-1} . Thus the optimum detector length should be about 1.0 mm. Detectors of this shape are conveniently stressed by applying the force perpendicular to the two faces where the contacts are located as is shown in Fig.2. The cross section to be stressed is thus $\sim 0.5 \text{ mm}^2$ for each pixel.

In order to apply a stress of 60 kg/mm^2 to an area of 0.5 mm^2 , a force of 30 kg is required. Using Eq.1-3 and the materials properties in Table I it is possible to select dimensions for the stress apparatus that give the required spring deflection of 100 μm . The number of springs n is a free parameter. As n increases the required spring length l decreases and the total thickness nt of the stack of springs increases. Examples calculated for stressing single detectors and linear arrays of 10 detectors using spring steel with a safety factor $Y/T_{\text{max}} = 3$ are

given in Table II. We have constructed a stress apparatus corresponding to example 2. The overall size of the stress apparatus for 10 detectors is not much larger than for a single detector.

III. Performance Tests

Test detectors were prepared from the Ge:Ga crystal¹² "LBL 82-head" with a Ga concentration $N_A = 1.2 \times 10^{14} \text{ cm}^{-3}$ and compensation ratio $\sim 10^{-2}$. A wafer was lapped to give parallel faces 0.5mm apart. It was etched to remove all lapping damage, ion implanted and gold-metallized on both sides and then annealed using the procedures described in ref.2. Rods 0.5mm wide were cut with one endface perpendicular to the rod axis and the other end beveled at 20 degrees. The average length was 1mm. The cut faces of these detectors were lightly etched. One of these so call "endfire" detectors was mounted between the pistons of the stress apparatus using 25 μm thick mylar sheets on each piston face for electrical insulation and 130 μm indium-coated beryllium copper sheets in contact with the detector electrodes for electrical contact as is shown in Fig.2. Both the beryllium copper and the mylar flow slightly and help to distribute the stress evenly.

There is significant infrared absorption on the sides of endfire detectors.¹² This absorption must be eliminated in order to unambiguously define the optical throughout of the stressed

endfire detector. We inserted $0.4 \times 0.5 \times 1.5 \text{ mm}^3$ blocks of stycast 2850FT¹⁶ epoxy on each side of the detector after the full stress had been applied, as is shown in Fig.2. These absorbers were glued with the same kind stycast to one of the beryllium copper pads to ensure a good thermal link to LHe temperature. Stycast 2850FT is strongly absorbing¹⁷ in the far infrared; the absorption coefficient $\alpha = 30 \text{ cm}^{-1}$ at $200 \mu\text{m}$.

Since the spring deflection in our apparatus is large compared with thermal contractions, the only change expected in the stress on cooling from room temperature to liquid helium temperature arises from the ~10% increase in Young's modulus for spring steel on cooling. This effect was calibrated by measurements of the deflection of a long sample of spring material at liquid nitrogen temperature, which is cold enough that the elastic properties should have approached their low temperature limit. The relation between deflection and force from Eqs. 1)-3) is

$$\delta = x l^3 / E t^3 = F l^3 / n w E t^3 \quad 4)$$

We used a stress apparatus with large, easily measurable deflections $\delta \geq 1 \text{ mm}$ and a calibrated spring to measure the dependence of detector conductance at 0°C on stress S . The detector temperature was controlled by enclosing it in a thin polyethylene bag and immersing it in an ice bath. The conductance ratio $\sigma(S)/\sigma(0)$ plotted in Fig.3 as a function of stress is a useful indicator of the applied stress at 0°C for an apparatus in which the deflections are too small to be measured conveniently.

It is independent of detector geometry. It should also be valid for Ge:Ga materials with other values of N_A , or for any germanium sample doped with shallow acceptors. In general, the conductivity is given by the product of the electronic charge, the mobility and the carrier density. Since all shallow acceptors are thermally excited at 0°C with or without stress, the carrier density is given by $N_A - N_D \approx N_A$ for low compensation material. The fractional change in conductivity with stress thus depends only on the mobility, which is phonon limited. It is then a property of Ge, not of the types or concentrations of shallow acceptors.

We used conductance measurements to place an upper limit on the changes in stress which take place when the stress distribution pads relax with time and repeated thermal cycling. The corresponding relaxation of the stress distribution pads was found to be less than 10 μm . In an apparatus with a spring deflection of 100 μm , this gives a stress relaxation of less than 10%. Using the known dependence of impurity ionization energy on stress³ this relaxation corresponds to an acceptable 2% shift in the long wavelength cutoff for photoconductivity.

The resistance measurement shown in Fig.3 provides a convenient method for selecting the screw position that will yield the desired stress value at low temperatures. The stress axis must first be corrected for the temperature dependence of Young's modulus for the spring material used. For our spring steel this correction corresponds to a 10% increase in stress on cooling.

Measurements were made of the absolute spectral responsivity of our stressed Ge:Ga endfire detector to confirm that the

anticipated performance had been achieved. This was done by using an apparatus described elsewhere¹² which evenly divides the output of a Fourier transform spectrometer between the stressed detector and a composite bolometer of known optical efficiency.¹² The electrical responsivity of the bolometer was determined by the conventional method¹² and used to calibrate the incident power. The throughput was limited to 4×10^4 sr-cm² (diffraction limited at 200 μ m) by blackened apertures, and the photon rate to 3×10^{11} s⁻¹ by cold black polyethylene and a neutral density filter. Several calibrating bolometers were used to check the reproducibility of the calibration method described above,¹² it was found to be better than 10%.

Measurements of absolute spectral responsivity given in Fig.4 show a relatively sharp onset of photoconductive response indicating uniform stress. The variation of the onset with stress is in agreement with the measurements of Kazanskii et al.³ The shape of the measured spectral responsivity above the peak is very similar to the measured absorption coefficient of the detector material¹² under the same stress. This suggests that the optimal detector length could be somewhat longer, especially for applications which require high responsivity over a broad spectral range.

In Table III we summarize the performance parameters of our detector under large 60kg/mm² stress and compare it with results obtained earlier² by Haller et al. Since low noise operation in a photoconductive detector is usually obtained by operating at a

fraction of the breakdown voltage, we have given data for V_b equal to 0.33, 0.50, 0.60 and 0.77 times the breakdown voltage. The higher values of bias were included to make a meaningful comparison with Haller et al.² and with Lutz et al.⁹ who reported breakdown fields of 0.54 V/cm and 0.83 V/cm respectively. In our samples, breakdown occurs at a voltage which corresponds to an average fields of ~ 3 V/cm in zero stress and ~ 0.4 V/cm in large stress. This dramatic decrease of breakdown voltage with stress is not understood in detail. The responsivity, and thus the G_n product are strong functions of the interelectrode distance which was very different for the three sets of data given in Table III.

IV. Conclusions

We have designed and tested a leaf-spring stress apparatus for Ge:Ga photoconductors. Good stress stability and uniformity combined with relatively small apparatus size are realized with this design. The stress that will be applied to the detector sample at LHe temperature can be determined easily at room temperature. One-dimensional stressed photoconductor arrays can be constructed using this design. The use of the endfire detector geometry yields a large responsivity with a relatively small detector volume.

Acknowledgments

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Table I. Properties of Spring Materials

Alloys	Young's Modulum	Yield Stress		
	E	Y	$E^{2/3}/Y$	$E^{1/3}/Y$
	(kg/mm ²)	(kg/mm ²)		
Spring Steel ^a	1.8×10^4	2.1×10^2	3.3	0.13
310 and 316 Stainless Steel ^b	2.1×10^4	2.1×10^2	3.6	0.13
Beryllium Copper ^b	5×10^3	7×10^1	4.1	0.24
Titanium Alloys ^b	1.2×10^4	1.6×10^2	3.3	0.14

^a The spring material tested in this investigation, E was measured at LN₂ temperature and Y was obtained from the manufacturer's specifications.

^b Typical values for moderately high strength materials.

Table II. Typical Spring Parameters for 0.5-x1.0-mm
Detectors Using Spring Steel

Example	1	2	3
Number of Detectors	1	1	10
Width $w(\text{mm})$	4.6	4.6	12.7
Number of Springs n	2	4	3
Length $l(\text{mm})$	11.5	15.2	15.4
Total Thickness $nt(\text{mm})$	2.7	4.5	7.2
Deflection $\delta(\text{mm})$	0.1	0.3	0.1

Table III. Summary of Performance of Stressed Ge:Ga Detectors
Operated at 2 K.

	Bias Field (fraction of breakdown)	Peak Responsivity (A/W)	$G\eta$
<hr/>			
This work	0.33	16	0.11
	0.50	38	0.26
	0.64	64	0.44
	0.77	102	0.70
Haller <u>et al.</u>	0.77	19	0.16
Lutz <u>et al.</u>	0.64	7	0.062

Figure Captions

Fig. 1. Cross section of the leaf-spring apparatus used to apply

uniaxial stress to a photoconductive detector:

a) carbon steel screw, b) leaf springs, c) saddle,
d) stainless steel support, e) steel pin, f) Ge:Ga
photoconductor assembly, g) drill rod pistons, and h)
carbon steel screw.

Fig. 2. Stressed endfire photoconductor assembly: a) stressing

pistons, b) 25 μ m thick mylar sheets, c) 130 μ m thick indium-
coated beryllium-copper, d) Ge:Ga endfire photoconductor,
e) stycast absorbers.

Fig. 3. Ratio of conductances measured at 0°C with and without
stress for Ge with shallow acceptors as a function of
uniaxial stress along a (100) axis.

Fig. 4. Absolute spectral responsivity of a Ge:Ga endfire

photoconductor with large stress: $N_A = 1.2 \times 10^{14} \text{ cm}^{-3}$;
sample length = 1.0mm; $T = 2.0^\circ\text{K}$; and $V_b = 6.0\text{mV}$.

XBL 8611-6483

FIGURE 1

XBL 8611-6486

FIGURE 2

XBL 8611-6481

FIGURE 3

XBL 8611-6482

FIGURE 4

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