Silicon photodiodes with integrated thin film filters for selective bandpasses in the extreme ultraviolet

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ABSTRACT

Silicon photodiodes which operate satisfactorily in the extreme ultraviolet (EUV) have been commercially available for the past few years. These photodiodes also inherently respond to radiation extending from the x-ray region to the near infrared, a property which is undesirable in many EUV applications. The addition of a thin film of a suitable filtering material to the surface of such a photodiode can accomplish the restriction of the sensitivity of the silicon to a much narrower band, or bands, in the EUV. This results in a rugged, yet sensitive photometer for applications in which dominant out-of-band radiation is present. Applications include plasma diagnostics, solar physics, x-ray lithography, x-ray microscopy, and materials science. Previous attempts to produce such devices have resulted in degraded shunt resistance with a corresponding increase in background noise. Prototype detectors have now been fabricated using directly deposited films of aluminum, aluminum/carbon, aluminum/carbon/scandium, silver, tin, titanium, titanium/yttrium/carbon, and titanium/zirconium/carbon without degradation of the noise characteristics of the uncoated photodiodes. Measured and theoretical sensitivity data will be presented, as will a discussion of relatively simple methods to reduce the x-ray response of such filtered detectors.

Key Words: photodiode, silicon, extreme ultraviolet, filter, detector

1. INTRODUCTION

Throughout the history of EUV technology, the development of optical detectors has presented special challenges. Detectors for this region must usually be operated in a clean, ultra-high vacuum environment, and must be free from interactive degradation in the presence of EUV radiation. Further, they should possess a low background noise level, to assist in the detection of relatively weak sources. Recent advances have enabled the use of specially made silicon photodiodes[1,2,3] in this spectral region. These new detectors are typically made with a very thin passivating silicon dioxide surface layer, are free from conversion losses within the silicon, and have proven to be relatively stable when exposed to radiation in the EUV[4], in contrast to designs resulting from earlier technology.

There remains, however, one significant shortcoming for certain EUV applications: the inherent broadband response which is characteristic of silicon, extending from x-rays to the near infrared. This broadband characteristic is often undesirable for an EUV detector, since continuum (such as synchrotron radiation) or multi-line (plasmas, etc.) sources, both common in this spectral region, can have large components of out-of-band radiation, which are often more intense than the radiation of interest.

A conventional approach to the alleviation of this concern with both silicon and photoemissive EUV detectors has been to use one or more suitable free-standing metallic thin film filters in conjunction with the detector to achieve a degree of spectral selectivity. The fragile nature of many materials in thin film form imposes limitations on this approach. It was suggested[2] that the spectral response of silicon photodiodes might be controlled with the direct deposition of such a filter on the detector itself. Prototype detectors, coated with evaporated aluminum or silver, were prepared then, and were found to exhibit spectral characteristics very close to those expected in the EUV[3]. Aluminum-coated silicon photodiodes were subsequently used in rocket-borne solar experiments[5]. However, the filter film depositions were made on fully packaged photodiodes, and it was found to be very difficult to avoid degrading device shunt resistance during film depositions. The physical separation of the diode elements on the front surface was small, and a small amount of evaporant in the separation region could bridge the gap. Generally this degradation resulted in a significantly increased level of "dark" noise compared to uncoated devices, limiting the potential usefulness of the coated photodiodes.

We report here on an improved technology in which filter films of several useful materials were applied during the photodiode fabrication process, at the wafer level. This approach, with a redesign of the photodiode configuration to eliminate the bridging problem described above, has essentially eliminated the degradation of the noise level over uncoated devices, without compromising the quality of the optical coatings.

2. EXPERIMENTAL

A schematic of the photodiode arrangement used in this study is shown in Figure 1. These photodiodes are fabricated on 100 mm diameter p^+ silicon wafers that have a p-type silicon epitaxial outer layer about 5 μm thick. The 1 cm^2 active area of the chips is produced by phosphorus/arsenic doping, followed by the thermal growth of a thin (15 nm) passivating surface layer of SiO_2. A deep p-n side junction, a p^+ channel stop, an n^+ guard ring were created by diffusions, as shown in Figure 1, before the active area formation. The purpose of the side junction is to improve the degree of discrimination against unfiltered radiation by isolating carriers resulting from radiation entering the sides of the structure from the main detection circuit. The entire front surface of each photodiode chip, except for a small region near the edges, was coated with the filter materials with little danger of degrading the device shunt resistance. One only needs to avoid coating the periphery of the chip.

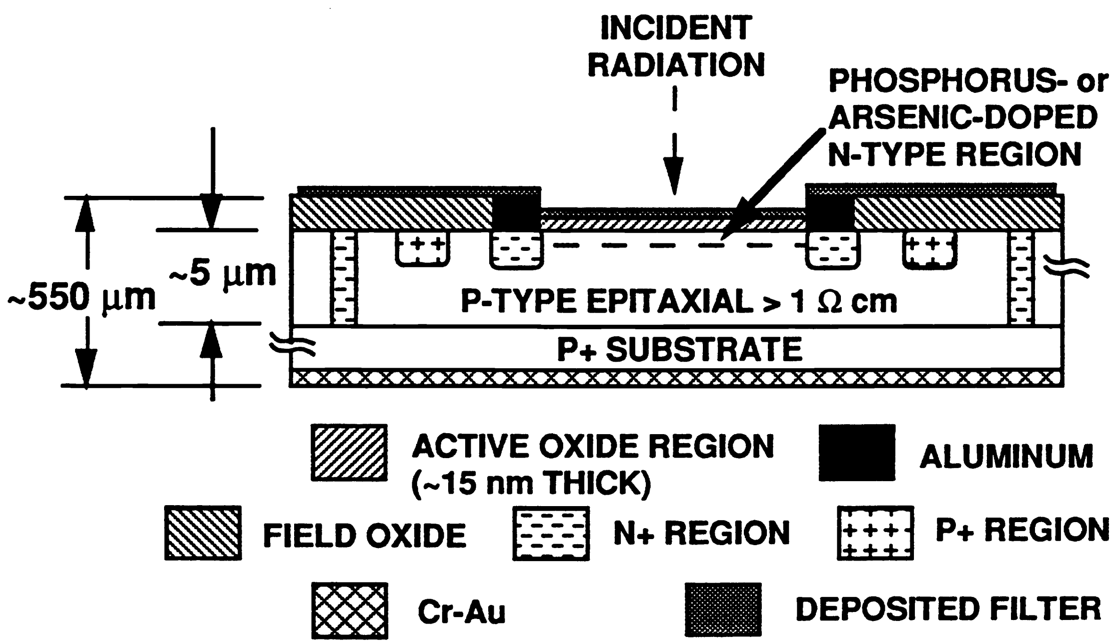

Figure 1. Schematic of the optically filtered EUV photodiodes prepared for this study.

Six coatings with useful bandpasses in the EUV were selected for study: aluminum, aluminum/carbon, aluminum/carbon/scandium, titanium, tin, and silver. These filters are commonly used in the region 0.1 to 80 nm, and have bandpasses ranging from 10 to 50 nm. The filtering material coatings were applied to the wafers by experienced suppliers of unsupported filters, so as to ensure that the optical quality was state-of-the-art.

Radiometric measurements of coated and uncoated photodiodes were made using the EUV detector standards calibration facility at the National Institute of Standards and Technology (NIST). This facility utilizes both the NIST electron storage ring synchrotron radiation source, SURF II, and a laboratory system equipped with a plasma source. The experimental systems and procedures at these facilities have been previously described[6]. Detector efficiency measurements were made by intercomparison with NIST working standards, which had been calibrated with the use of a rare gas ionization chamber (an absolute detector). Uncertainties (two standard deviations) in the device efficiencies derived from these measurements were in the range of 7% to 22%, depending on wavelength, as described in Ref. 6.

3. RESULTS

The results of spectral efficiency measurements of the coated photodiodes are shown in Figure 2 as discrete data points. Also shown are the calculated photodiode efficiencies based on the conversion efficiency of silicon and the transmittance of the thin film coating(s), including the 15 nm thick passivating silicon dioxide layer. A conversion efficiency of one electron-hole pair per 3.63 eV of photon energy was used for silicon. The optical constants used in the transmittance calculations are from Henke et al.[7]. These calculations assume negligible reflective loss (at normal incidence) in this spectral region. Because the density of thin film coatings can vary with different deposition methods, the thicknesses of the coatings were adjusted from their stated deposition thicknesses in order for the calculations to better fit the measured data. It can be seen that there is reasonable agreement between the resulting calculated values and the measured device efficiencies.

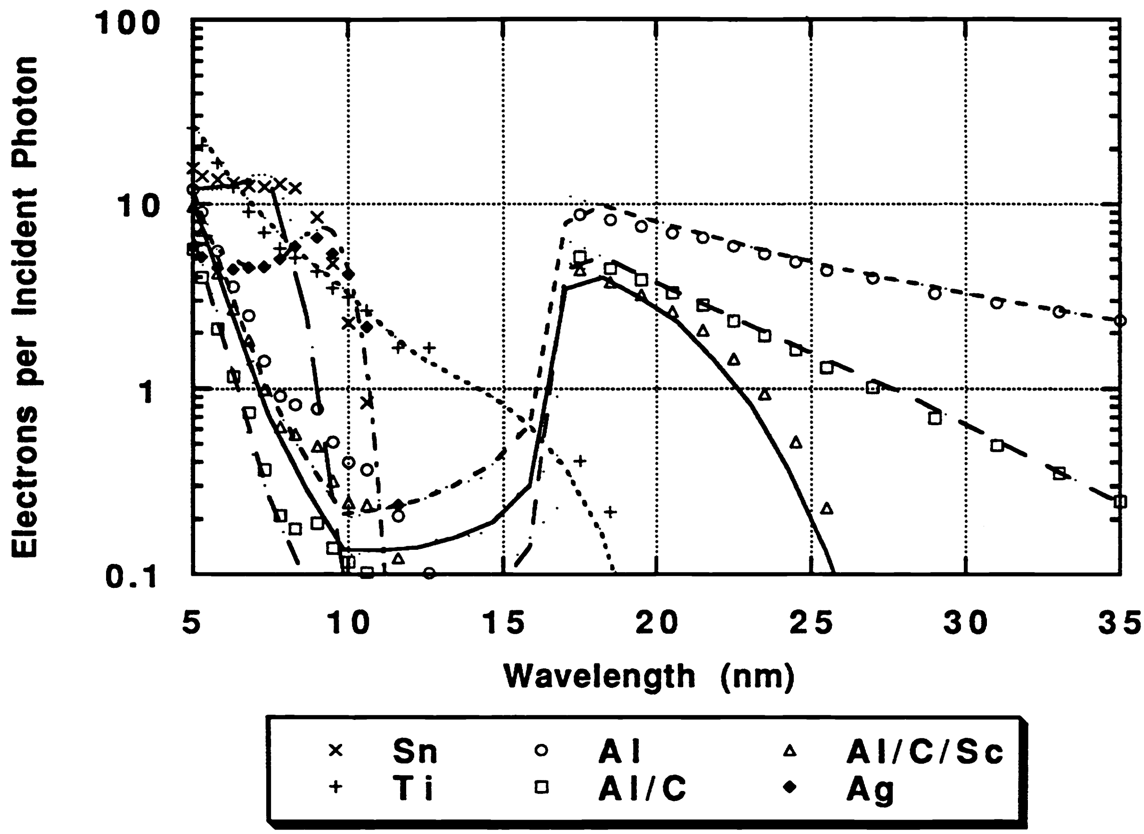

Figure 2. Calculated (curves) and measured (points) efficiencies of silicon photodiodes coated with several common EUV filtering materials. Calculations included losses in the filters, and in the SiO_2 passivating oxide on the photodiode surfaces. The effective film thicknesses used in the calculations are given in Table 1.

Table 1. **The thickness of the individual film components used in the calculations shown in Figure 2. In all cases, the absorption loss from a layer of silicon dioxide 15 nm thick was included. The thicknesses shown in parentheses are for an assumed layer of aluminum oxide, also included in the calculations.**

Film Components	Component Thicknesses (nm)
Al / C / Sc	(5) / 150 / 40 / 50
Al	(5) / 150
Al / C	(5) / 200 / 50
Ti	180
Sn	300
Ag	290

Figure 3 shows the measured and calculated response of photodiodes coated with combinations of Ti, Y, Zr and C, giving a bandpass with a natural short wavelength cutoff in the vicinity of 5 nm. These designs have a bandpass similar to that of a Be-coated photodiode, whose measured response is shown for comparison., but do not present the problems with toxicity found with Be.

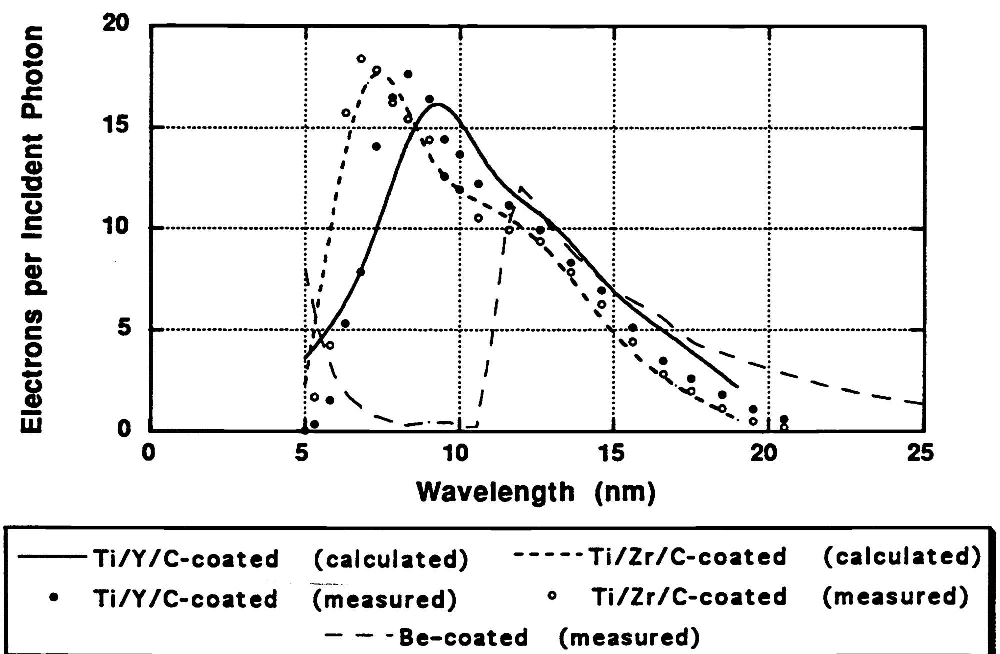

Figure 3 The measured and calculated response of silicon photodiodes coated with Ti/Y/C (6 nm/210 nm/55 nm) or Ti/Zr/C (6 nm/195 nm/50 nm) with the response of a photodiode coated with Be (400 nm) shown for comparison.

Dark current for each chip was measured before and after the filter coatings were deposited, and in all cases there was no significant increase in the measured value. Typical measured dark current values before or after coating were about 100 fA, with noise variations of this current about an order of magnitude less.

Additional tests of the coated photodiodes were made to determine the magnitude of any visible light leaks through the nominally opaque filter coatings. The procedure consisted of scanning the active areas with a He-Ne laser beam about 1 mm diameter to measure the rejection of visible light, and to detect the presence of any pinholes in the coatings. Typical rejections of five to six orders of magnitude relative to unfiltered response were found. This represents a significant improvement over photodiode structures without the special side junction. Most coatings were found to have a few pinholes near the edges related to processing the chip. We anticipate that better deposition and handling techniques should provide more pinhole-free coatings.

4. X-RAY REJECTION TECHNIQUES

It would be useful in some applications to improve the isolation of the response of filter-coated silicon photodiodes by reducing their response to x-rays. Foremost among obvious environments which would benefit would be those involving synchrotron radiation from machines with energy levels above 500—1000 MeV. A relatively simple method, given below, could be employed to reduce the x-ray response.

The addition of a single reflection from a suitable mirror used at an appropriate angle of incidence will surely prevent x-ray radiation from reaching the silicon. One can vary the mirror angle and/or material as well as the filter material to tailor the response toward that desired. Figure 4 shows the schematic of a simple arrangement in one possible configuration which might be appropriate for some applications.

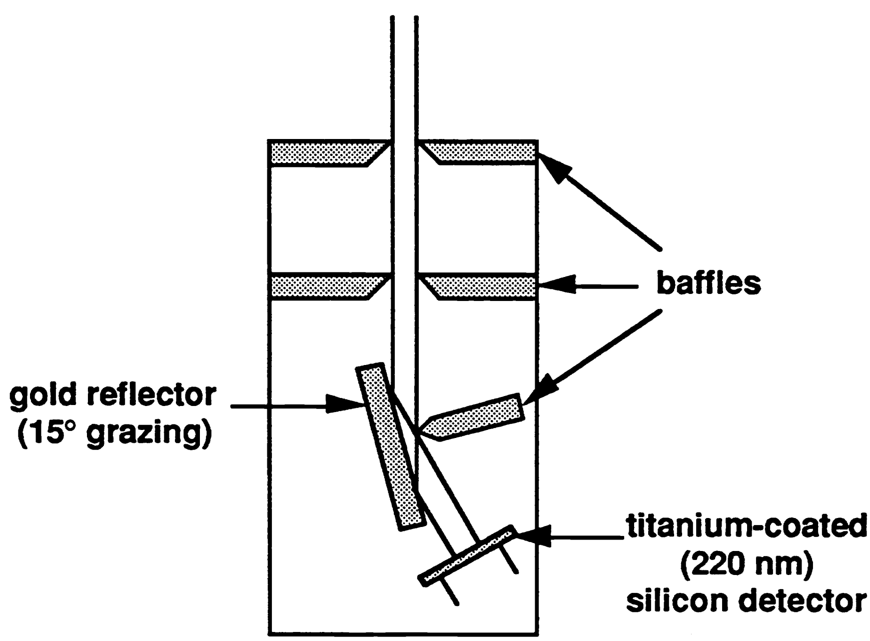

Figure 4. Example of a single reflection photometer design configured to reduce response to x-rays.

Figure 5 shows the calculated efficiency of a detector assembly with the configuration shown in Figure 4, and of a bare silicon detector without the filter film and the mirror.

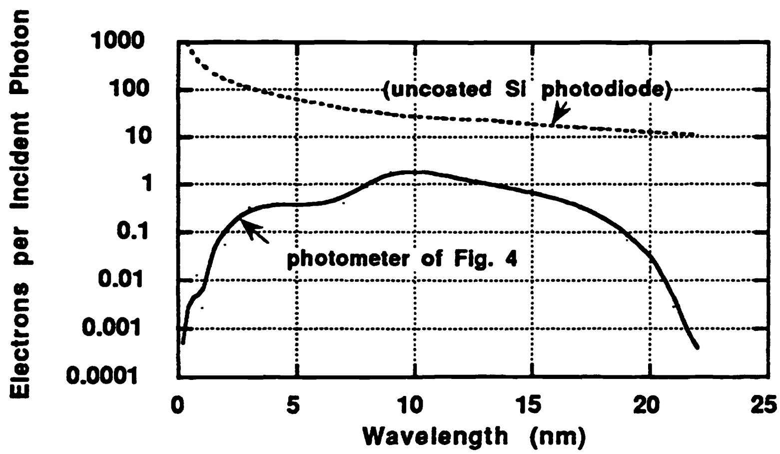

Figure 5. The calculated efficiency of a single-reflection photometer of the type shown in Fig 4. The spectral bandpass can be modified by choices of reflector material, grazing angle, and filter material. The calculated efficiency of an uncoated silicon photodiode alone is also shown.

A second example of a narrower bandpass configuration is shown in Figure 6. Here both the filtering film and the mirror are silver, and the grazing angle is 20°.

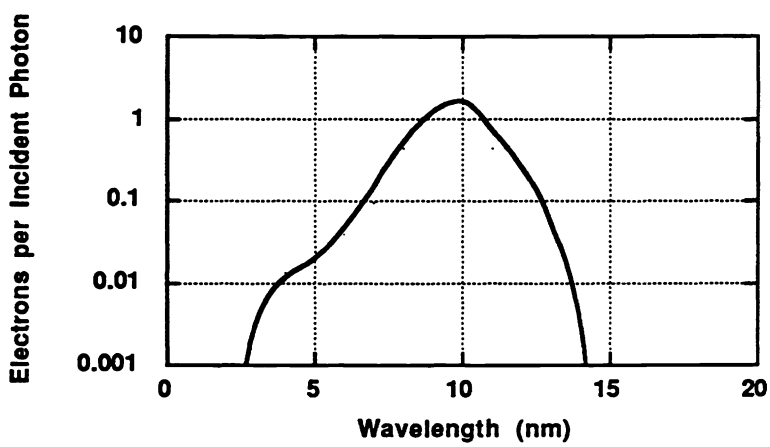

Figure 6. The calculated efficiency of a single reflection photometer utilizing a silver mirror and a silver coating on the surface of a photodiode. The calculations do not include surface films.

Another technique that rejects x-ray radiation is to reduce the thickness of the active silicon layer (the 5 μm layer shown in Fig. 1). The thickness of silicon required for 1/e absorption (unit optical depth) of incident radiation is shown in Figure 7 as a function of wavelength. These calculations were made using absorption coefficients for crystalline silicon from the literature[8]. Making the active silicon layer about 1 μm thick is technically possible by using silicon-on-insulator wafers. With this silicon thickness, the x-ray radiation less than 2 nm wavelength would be largely rejected, because most of those photons would pass through the active silicon layer without being detected.

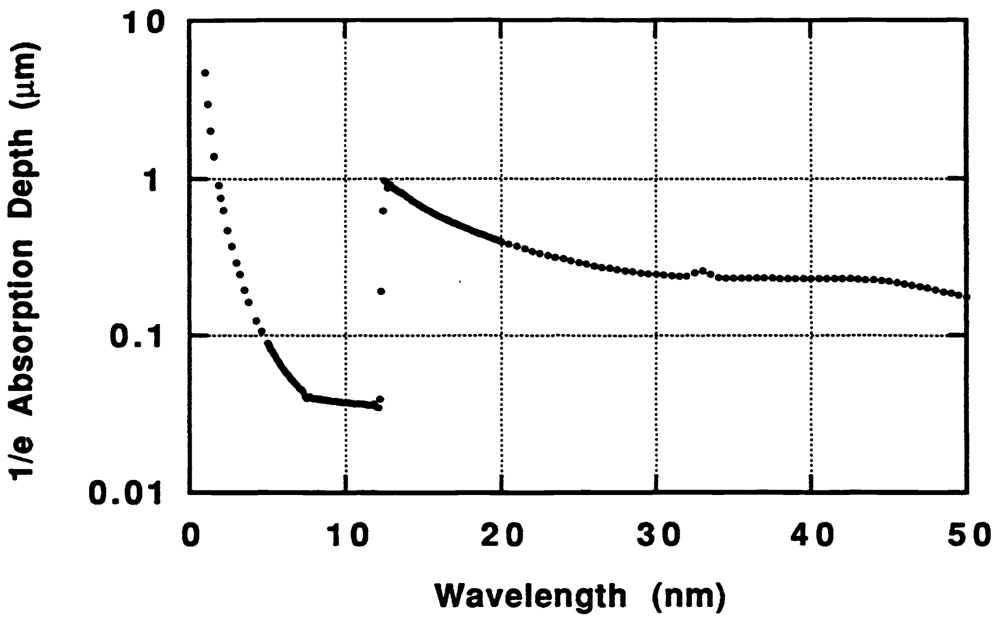

Figure 7. Calculated 1/e absorption depth in silicon as a function of wavelength.

5. CONCLUSIONS

A processing technology for producing high quality silicon photodiodes with integrated filters for selective bandpasses in the EUV has been demonstrated. The results of efficiency measurements on the completed devices indicate good agreement with modeling calculations, which were based on the conversion efficiency of the silicon and the optical properties of the filter materials. Photodiodes coated with appropriate filtering materials may find applications in diverse EUV disciplines, such as plasma diagnostics, solar physics, x-ray lithography, x-ray microscopy, and materials science, and can reduce the dependence on relatively fragile unsupported metallic filters for spectral discrimination.

The spectral selectivity of these coated photodiodes may be improved with the addition of an appropriate reflector, creating a detector assembly with an even narrower bandpass. The use of an appropriate grazing incidence reflector in conjunction with the filter coating maintains a relatively high peak detection efficiency, while producing orders of magnitude discrimination against out-of-band radiation, both shorter and longer in wavelength. Alternately, the filter coating may be applied on a photodiode fabricated with a thin (~1 μm) active epitaxial silicon layer, so that radiation of less than about 2 nm wavelength simply passes through the detector, thus reducing response from the x-ray portion of out-of-band radiation.

6. ACKNOWLEDGMENTS

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