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Diamond photodetectors for next generation 157-nm deep-UV photolithography tools

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Abstract

Next generation photolithography stepper tools will operate at 157 nm and require robust solid state photodetectors to ensure efficient operation and facilitate direct beam monitoring for photoresist exposure dosimetry. There is currently no commercial detector system able to fully meet all the demanding requirements of this application. Diamond, which is intrinsically visible blind and radiation hard, is an obvious candidate for consideration. In this paper we report the results of the first study to assess the viability of thin film polycrystalline diamond photodetectors for use in 157 nm F2-He based laser lithography tools. Co-planar inter-digitated gold photoconductor structures were fabricated on free standing thin film diamond and exposed to pulses from an industrial F2-He laser in the fluence range 0-1.4 mJ cm-2. The electrical and optical characteristics of the devices have been measured and are compared to the response of a standard vacuum photodiode. The suitability of the diamond devices for use at 157 nm is discussed.

Keywords: Diamond; Photoconductor; Photodetector; Photolithography

1. Introduction

The gate density in silicon integrated circuits quadruples every 3 years, a phenomenon described by Moore's Law. Device structures are formed by projection lithography using a step and repeat machine (known as a ‘stepper’), each costing several million dollars. The ultimate feature size achievable, and hence the gate density, is limited by the wavelength of the radiation used to illuminate the mask, which in turn projects the desired circuit image onto the silicon wafer. In pursuit of ever smaller feature sizes it has been necessary for the semiconductor industry to move from mercury UV lamps operating at the a-line wavelength, to i-line and more recently to the shorter wavelength pulsed 248 nm light available from KrF filled excimer lasers. Steppers utilising 193 nm light from ArF filled excimer lasers are now being introduced and SEMATECII, a forum comprised of the major silicon device manufacturers world-wide, have designated 157 nm as the route to realise device structures of 100 nm and below [1]. A very bright source for this wavelength is the molecular fluorine laser, often misleadingly referred to as an excimer laser because with a suitable change of optics and gas mix it operates in the same device as rare gas halide lasers [2]. A pressing problem in the development of 157-nm steppers is the treed for a simple. robust solid state photodetector that can

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operate effectively at this wavelength for up to 107-108 laser pulses. Such devices are required for control purposes such as measuring the total UV exposure given to the photoresist covering the silicon substrate and monitoring UV beam homogeneity. Silicon based CCD devices are currently used for lamp (g and i-line) and laser (248 nm) light monitoring, but can suffer unacceptable loss of performance after only 10^{-5} laser pulses at 248 nm in some applications [3]. Moreover, light penetration into the active region of the silicon device becomes difficult at 193 nm and impossible at 157 nm. It is the lack of a solution to beam monitoring at 157 nm that provides the real prospect of the acceptance by the semiconductor industry of device technology based upon a completely new electronic material.

The extreme properties of chemically vapour deposited (CVD) diamond suggest that it may be a suitable candidate material for this application. Photodetectors based on this material should be both radiation ‘hard’ and intrinsically visible blind whilst being sensitive to the deep UV wavelengths that silicon devices fail to monitor [4]. Previously we have shown that effective photoconductor structures can be fabricated from thin film polycrystalline diamond by combining careful device design with surface treatments to reduce the influence of the inherently defective nature of this form of diamond [5]. In this paper we present results of the first study to assess the potential of CVD diamond photoconductive structures for use in the next generation of photolithography stepper tools operating at 157 nm.

2. Experimental

All photodetecting devices were fabricated on free standing polycrystalline diamond grown by plasma-enhanced CVD. Films were approximately 100 μm in thickness and exhibited a random crystal morphology with typical grain sizes in the range 20-40 μm. Raman spectroscopy was carried out using a red He-Ne excitation source and showed only the sharp characteristic peak of diamond at 1332 cm^{-1} with a very low background and no evidence of any other structure; further details have been given elsewhere [6]. Prior to contact formation the diamond was laser cut into 4 × 4 mm tiles which were then subjected to an acid treatment to remove surface contamination and residual sp^2 [7]. This treatment also removes the p-type conductive layer sometimes present at the surface of CVD diamond and leaves it in an oxidised state. Electrode structures consisting of 15-co-planar gold interdigital finger pairs on a 25-μm mark-space ratio were deposited to a thickness of ~ 300 nm by thermal evaporation on the growth surface of the CVD diamond samples. Each detector incorporated two 100 μm square pads to allow electrical contact. The samples were then subjected to a two step methane-air treatment, which we have previously shown can improve the electrical characteristics of this type of device structure [8]. Finally, the devices were mounted and wire-bonded to industry standard T05 type packages to facilitate detector evaluation. Typical examples of the electrode structure and a completed device are shown in Fig. 1 (a, b), respectively.

Device I-V characteristics were measured using a Keithley K487 pico-ammeter and stabilised DC power supply. This instrument was also used together with an optical system (150-W Xe lamp, nitrogen purged Amko International monochromator with order sorting filters) to assess the steady state spectral characteristics of the devices in the range 180-800 nm. Detector response to 157 nm laser radiation was assessed using a 50 Ω impedance measurement circuit in series with a 50 Ω 500 MHz digital storage scope (Tektronix TDS 3052).

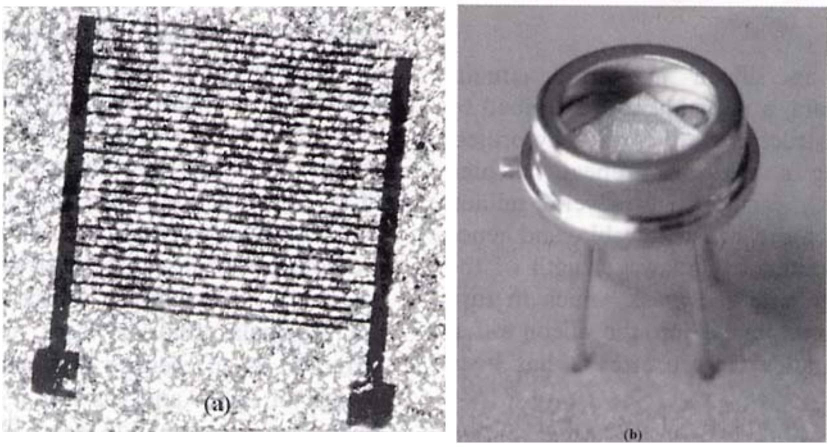

Fig. 1. (a) Optical micrograph of typical CVD diamond used to fabricate the photodetectors, (b) example of a completed device mounted in device can for testing.

A Lambda Physik LPX-200 Excimer laser system operating with a He-F_2 gas mix and modified optics was used to illuminate the detectors with 157-nm laser pulses. The beam was conveyed to the detectors via a tube purged with nitrogen and terminated with a simple variable iris. Laser power was varied in the range 0-1.6 mJ cm^{-2} using the laser power supply and the pulse power was measured using a Molectron EPM1000 detector and power meter. Measurements indicated that the laser power at 157 nm varied linearly with EHT over the range 22-26 kV. For comparison with the diamond detectors the laser pulse shape and intensity was also measured using a vacuum photodiode (VPD) operating at 0.2-1.7 kV.

3. Results and discussion

Two nominally identical devices were tested during these experiments and are referred to as D1 and D2 in the following discussion. The low light and dark current I-V characteristics of each device were measured between ± 10 V and found to be ohmic in character. D1 had a dark current ~ 3.5 times that of D2 which may reflect small differences in the interface quality at the contacts or some variation in surface leakage current. However, all dark currents were *G* 1 pA at the maximum applied voltage and there was no significant asymmetry in this value. It can therefore be expected that these devices will function in the photoconductive mode, with a gain level that increases linearly with the applied field. This may not be true at high levels of illumination where space-charge limited current effects may appear [9].

The steady state spectral responses of each device were measured over the 180-800-nm range and the results are shown in Fig. 2. The characteristics are very similar and show the sharp diamond band edge at 220 nm and a high deep UV/visible (200/550 nm) discrimination, at approximately 5-6 orders. It should be noted that these devices were subjected to surface treatments, described elsewhere [8], which can significantly improve the electrical and spectral characteristics over those of untreated devices. Due to experimental system limitations the spectral characteristics do not extend to 157 nm. However, a pessimistic extrapolation of the characteristics presented in Fig. 2 suggests that the UV/visible discrimination would still be at least 3 orders of magnitude at this wavelength.

The response of the devices to 157 nm laser pulses is shown in Fig. 3, compared to the response of a vacuum photodiode, the data having been normalised to aid comparison. The VPD shows the presence of two clearly defined peaks. It is well known that 157-nm F_2 laser pulses can be accompanied by a visible discharge in the red region of the spectrum [2,10]. This was confirmed by examining the detector signal, having placed filters between the laser output and the detector itself. When a simple glass filter was used, the most prominent peak was removed, leaving the smaller peak. In turn, this smaller peak decreased in intensity with the insertion of number of paper sheets and was completely removed by cardboard. The red part of the pulse arises from unwanted optical transitions within the F2-He gas mix. The magnitude of the red wavelength component compared to the 157-nm lasing transition, depends on a number of factors including the laser design, gas pressure and operating conditions. It was measured at approximately 50% of the total output for the laser used here. The red component accompanying the main pulse cannot easily be filtered out and this highlights the importance of using a detector that is intrinsically blind to visible wavelengths. At a fluence of ~ 1.5 mJ cm^{-2}, the diamond detector response to the 157-nm part of the pulse was typically a few volts and in contrast to the VPD, very little of the red component is 'seen' by these detectors as is clearly shown in Fig. 3. The pulse duration at full-width-half-maximum (FWHM) for this laser is expected to be 15-20 ns and this is in close agreement with the values obtained from the diamond detectors, at approximately 18 ns. However, the value obtained from the VPD is approximately 38 ns. The rise times of the two detector types are quite similar and the VPD is clearly capable of responding to shorter pulses as evidenced by its response to the red pulse, which has a FWHM of ~ 10 ns. The most likely explanation is that the 157-nm radiation may be causing some fluorescence in the VPD window material, which is effectively lengthening the duration of the monitored pulse.

The gain of the diamond devices varies linearly with applied bias as shown in Fig. 4. This confirms that the operation is primarily photoconductive at the pulse

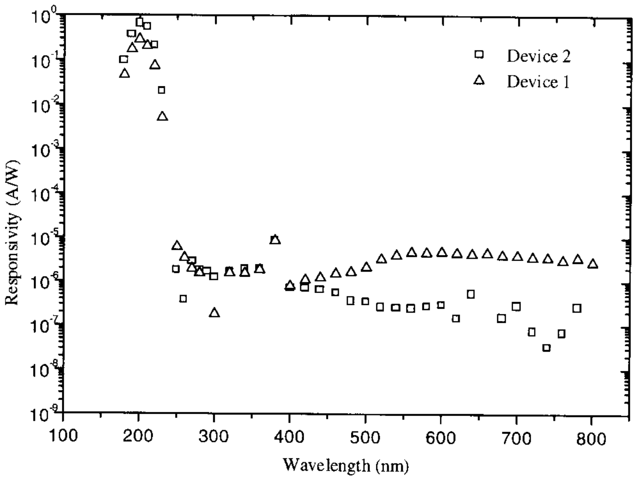

Fig. 2. Spectral response of devices D1 and D2 shown normalised to the response of D2 at 200 ran.

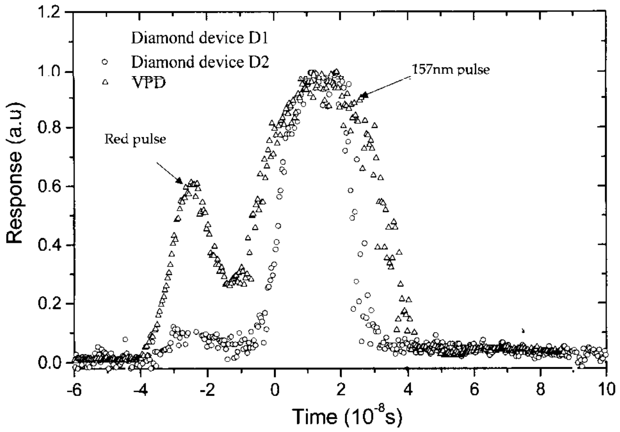

Fig. 3. High resolution measurement of the response of diamond photoconductors and a vacuum photodiode to the output of a 157-nm molecular fluorine laser. The data have been normalised in each case.

fluences tested here (up to ~ 1.5 mJ cm^{-2}). To study the device response as a function of incident laser fluence, the peak device voltage was recorded for pulse fluences in the range 0-1.4 mJ cm^{-2}. The results for device D2 are shown in Fig. 5; nearly identical data was obtained for device Dl. Both devices show a large linear response up to approximately 0.6 mJ cm^{-2} after which the response curve becomes strongly asymptotic to a value of approximately 9 V at approximately 1.4 mJ cm^{-2}. This is most likely to be due to the intrinsic characteristics of the measurement circuit, which acts as a potential divider formed from the photoconductor resistance and the 50 Omega input impedance of the digital scope. For large photoconductor resistance (lower UV fluences) the circuit response is close to linear. However, at sufficiently high laser fluences the voltage dropped across the scope saturates at the bias voltage [11].

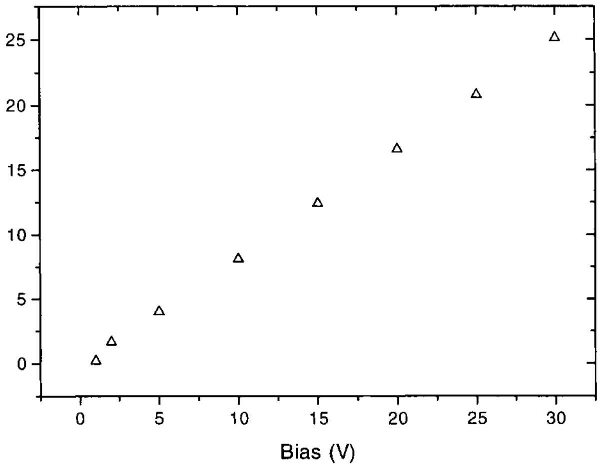

Fig. 4. Peak output for typical diamond device as a function of applied bias under illumination by 157-nm laser pulses at a fluence of 1 mJ cm-2.

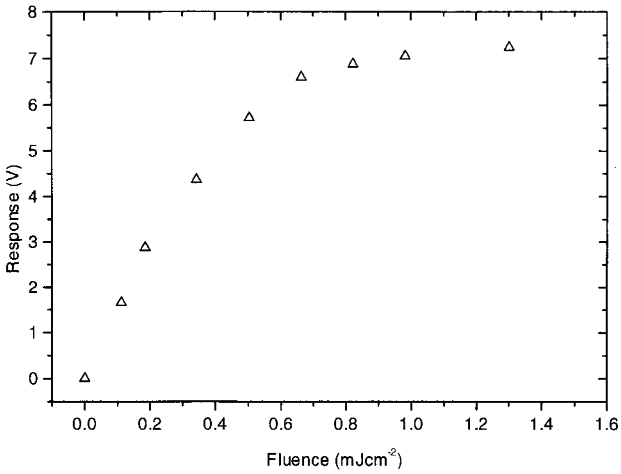

Fig. 5. Device response (D2) to increasing pulse fluence in the range 0-1.4 mJ cm^{-2} at a fixed device bias of ~ 10 V.

4. Summary

Photodetecting devices operating in the photoconductive mode have been fabricated from thin film CVD diamond. The effectiveness of these detectors for use in molecular fluorine laser systems operating at 157 nm has been assessed for the first time. The devices show a good response over the fluence range 0-1.4 mJ cm^{-2} and appear to be capable of following the temporal development of the laser pulse. Device gain was found to be linear with applied bias over the range tested (± 30 V) with a sensitivity of ~ 10 V/mJ cm^{-2} over the linear portion of Fig. 4. These devices seem highly suited to applications within the 157-nm based stepper tools that are required by the semiconductor industry for next generation IC fabrication. The long-term lifetime of these particular devices has not yet been fully assessed at 157 nm. However, during the course of these tests the devices were subjected to between 10^4 and 10^5 pulses with no obvious degradation in characteristics. Furthermore, very similar devices have remained operational for up to 10^7 pulses of 193-nm excimer laser radiation at similar fluence levels, in experiments to be reported elsewhere [12]. Despite this, it remains important to conduct long term tests of the devices at 157 nm, since this wavelength gives rise to direct bandgap absorption, whereas 193 nm is absorbed via indirect bandgap transitions, potentially leading to differing damage mechanisms.

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