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Experimental and theoretical investigation of millisecond-pulse laser ablation biased Si avalanche photodiodes

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ABSTRACT

Bump formation was observed for the first time on the surface of biased Si avalanche photodiodes (APDs) fabricated using millisecond-pulse laser ablation, and the mechanism of the phenomenon was studied experimentally and theoretically. Surface maximum temperatures and damaged areas were tested under different laser pulse durations. The surface maximum temperature was ~1500 K, which is lower than the melting point of Si when the laser pulse duration and energy density were 1.0 ms and 50 J/cm^2, respectively, but there was a damaged area on the surface. A longitudinal temperature distribution simulation showed that the laser ablation first occurred at the PN junction of the APD, and the mechanism of the phenomenon was Joule heating. This result differs significantly from results obtained for laser ablation of other photodetectors.

With the development of photoelectric technology, photodetectors have been widely used in both military and civilian fields [1,2]. However, laser energy can be strongly absorbed by the photodetector because it is located at the focal plane of the optical system, making photodetectors more susceptible to damage than other devices in an optical system [3]. Therefore, laser-induced damage of photodetectors has been a major concern of the international scientific community. As early as the beginning of the 1970s, changes in photoelectric performance parameters, such as dark current, photocurrent, and responsivity, caused a by nanosecond-pulse laser-irradiated transistor had been researched, and the redistribution of the doping ions was observed via electron microscope [4,5]. About 20 years later, the relationship between the decrease in electrical properties and the laser-induced damaged surface morphology was further studied by Watkins et al., who thought that the depletion layer defect caused during melting was the main reason for electrical performance degradation [6]. Based on Watkins's research, the relationship between the decrease in electrical properties and the laser-induced photodetector's physical damage was also researched [7]. Compared to other detectors, an avalanche photodiode (APD) has the advantages of high quantum efficiency, small size, insensitivity to magnetic fields, low operating voltage, and ability to work at room temperature. Consequently, this photodetector has been used most widely [8–11]. In this Letter, bump formation was observed for the first time on biased Si APD surfaces fabricated using millisecond-pulse laser ablation. To analyze the mechanism of this phenomenon, we report on experimental and theoretical research on millisecond-pulse laser ablation biased Si APDs. Our study revealed a very interesting phenomenon in that the laser ablation first occurred at the PN junction instead of on the biased Si APD surface. We sought to determine the reason for this and confirmed it via micromorphology testing and longitudinal temperature distribution simulations and found that the mechanism responsible for the phenomenon was Joule heating.

The experimental arrangement is shown schematically in Fig. 1. We used a flash-lamp-pumped Nd:YAG laser with a pulse duration of 0.5–3 ms at a fundamental wavelength of 1064 nm with a Gaussian output waveform. The pulse repetition rate could be varied manually from 1 to 10 Hz by changing the firing rate of the flash lamp. An attenuator with an attenuation rate of 10 was located at the exit of the laser, and a 2:1 beam-splitter was placed after the attenuator. The TEM$_{00}$ mode laser beam was focused by a lens with a 20-cm focal length. The beam spot size determined by the slit scan technique was of the order of 360 μm at the focal spot and was independent of the pulse repetition rate. The Si APD was biased with 180 V when it was irradiated by the millisecond-pulse laser.

When the pulse duration was 1.0 ms and the energy density was 50 J/cm^2, the morphology was measured via confocal microscopy (Zeiss Axio CSM 700), as shown in Fig. 2. Compared to other

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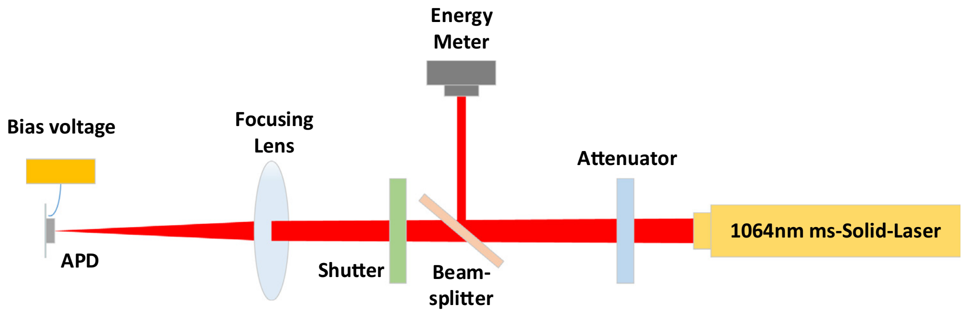

Fig. 1. Schematic of the experimental configuration.

Fig. 2. Micromorphology of a laser-ablated Si APD.

areas, the ablation areas are raised, not sunken. The phenomenon of bump formation indicated that the inner temperature was higher than the melting point of silicon.

The maximum temperature and the laser ablation areas of the APD surfaces were measured by an infrared thermometer and a 50× optical microscope, respectively, as shown in Fig. 3. This figure shows that the maximum temperature and ablation areas decreased as the pulse duration increased. The maximum temperature of ~1500 K when the pulse duration was 1.0 ms and the energy density was 50 J/cm^2 was still less than the melting temperature of silicon. However, interestingly, the surfaces of the APD were ablated. We believed that this phenomenon could be explained only by the internal structure of the APD and its working mechanism under bias [12,13].

The test samples were Si APDs with the reach-through structure shown in Fig. 4. The surfaces of theses detectors are coated with a standard antireflection film, and the active area is 0.5 mm^2.

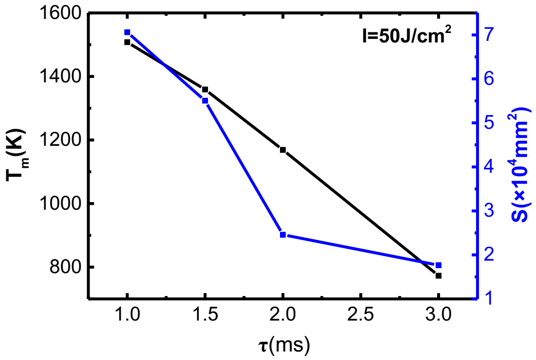

Fig. 3. Laser ablation areas and surface maximum temperature versus pulse duration.

From the surface of the bottom layer, an APD successively includes a heavily doped n-type region, a p-type region, an intrinsic region, and a doped p-type region. When a high reverse bias applied at the two ends creates an inner electric field, the voltage drop is mainly located at the PN junction. The incident intense pulse laser passing through the intrinsic or absorption region creates electron–hole pairs along its track. The charges move in opposite directions under the influence of the inner electric field, and a reverse current is formed. The electrons move toward the n-region, which is characterized by a very high electric field intensity E, which is where avalanche multiplication takes place, and the reverse current increases dramatically. We assume that the reverse current is mainly a result of this electron movement and the reverse saturation current density J_s can be expressed as [14]

$$J_s = q\left(\frac{D_n}{\tau_n}\right)^{\frac{1}{2}}\frac{n_i^2}{N_A} \propto T^{3+\frac{\gamma}{2}}\exp\left(-\frac{E_g}{kT}\right), \tag{1}$$

where q is the electric charge of an electron; D_n and τ_n are the diffusion coefficient and diffusion time, respectively; N_A is the p-type area acceptor concentration; γ is a constant; E_g is the Si band gap; T is the absolute temperature; and k is the Boltzmann constant. Eq. (1) shows that the reverse saturation current density exponentially increases with temperature.

For a multilayered structure, the heat conduction equation under laser irradiation is as follows:

$$\rho c\frac{\partial}{\partial t}T(r,z,t) = \frac{1}{r}\frac{\partial}{\partial r}\left(rk\frac{\partial T(r,z,t)}{\partial r}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T(r,z,t)}{\partial z}\right) + q(T,r,z,t) + Q(T,r,z,T), \tag{2}$$

where $q(T,r,z,t)$ is the laser heat source and $Q(T,r,z,t)$ is the Joule heat source. According to the analysis of the electric field intensity, the Joule heat is mainly produced in avalanche areas and is given by

$$\begin{aligned} Q_{p^-}(T,r,z,t) = {} & \left(\frac{V(z)}{z}(q\mu_p(T)(p(T,r,z)\frac{V(z)}{z} - \frac{kT}{q}\nabla p(T,r,z)\right) \\ & + q\mu_n(T)\left(n(T,r,z)\frac{V(z)}{z} + \frac{kT}{q}\nabla n(T,r,z)\right) \\ & + \frac{(E_g(T)+3kT)\left(\frac{\Delta n(T,r,z)}{\tau_n} + \frac{\Delta p(T,r,z)}{\tau_p}\right)}{2})g(t), \end{aligned} \tag{3}$$

where $V(z)$ is the relation between the voltage of the avalanche area and the position of the axis; $\mu_p(T)$ and $\mu_n(T)$ are the temperature-dependent mobility of holes and electrons, respectively; $p(T,z,t)$ and $n(T,z,t)$ are the hole and electron concentrations, respectively, which vary with temperature and position; $\nabla p(T,z,t)$ and $\nabla n(T,z,t)$ are the hole and electron gradients, respectively; $E_g(T)$ is the temperature-dependent energy gap; and $\Delta p(T,r,z)$ $\Delta n(T,r,z)$ are the photocarrier concentrations, given by the expression