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EXCIMER LASER PROCESSING OF BACKSIDE-ILLUMINATED CCDS

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ABSTRACT

An excimer laser is used to activate previously implanted dopants on the backside of a backside-illuminated CCD. The controlled ion implantation of the backside and subsequent thin layer heating and recrystallization by the short wavelength pulsed excimer laser simultaneously activates the dopant and anneals out implant damage. This improves the dark current response, repairs defective pixels and improves spectral response. This process heats a very thin layer of the material to high temperatures on a nanosecond time scale while the bulk of the delicate CCD substrate remains at low temperature. Excimer laser processing of backside-illuminated CCDs enables salvage and utilization of otherwise nonfunctional components by bringing their dark current response to within an acceptable range. This process is particularly useful for solid state imaging detectors used in commercial, scientific and government applications requiring a wide spectral response and low light level detection.

BACKGROUND

A number of image-gathering detectors use charge coupled devices (CCDs) with varying degrees of sensitivity and resolution. CCDs are solid state electronic imaging devices which read out image charges from wells in an array of pixels. CCDs designed for solid-state cameras, such as camcorders, are in great demand and are widely available. They have been designed to provide adequate performance when viewing brightly illuminated scenes. However, in astronomical, scientific and military applications their spectral response, dark current, and other characteristics are not satisfactory. Excimer laser processing of backside-illuminated CCDs will be shown to overcome these deficiencies.

Spectral Response:

To overcome the limitations of imaging through the polysilicon gates that necessarily cover all of the sensitive pixel array, it would be desirable to illuminate the CCD from the backside if the silicon substrate were thin enough. In other words, a solution to obtaining better light sensitivity would be the thinning of the backside of the CCD to a total thickness of roughly 10 microns and illumination from the backside. When the silicon substrate upon which the array resides is made thin enough to permit short-wavelength light (blue and ultraviolet) to penetrate into the active regions of the device, improved spectral response has been obtained. However, for a backside-illuminated CCD, the electrical characteristics of the shallow region near the back surface dominate the CCD response to short wavelength photons. Silicon develops a thin native oxide ($<$ 30 Å thick) that can contain enough trapped positive charge to deplete a region several thousand Angstroms deep into the CCD. The absorption depth for high energy (UV or blue) photons in silicon is very short (about 30 Å for 250 nm light and about 900 Å for 400 nm light). Therefore, photogenerated electrons created in this region can drift toward the Si/SiO_2 interface and become trapped or recombine thereby drastically reducing the quantum efficiency in the UV and blue.

One method of accumulating the backside of the CCD is by ion implantation of the backside and subsequent heating to activate the dopant. Initially, only a fraction of the implanted dopant atoms reside in locations in the crystal which are electrically active. Thermal energy is provided to permit the migration of dopant atoms into active sites. The obstacle that must be overcome by fabricators when this approach is relied on is that the backside doping process (and heating) occurs after all frontside device fabrication. A large temperature elevation of the frontside circuitry at this point in the process can cause deleterious effects. For example, backside doping of a silicon substrate with boron has been attempted to enhance the spectral response and suppress the dark current of CCD detectors. Boron implantation is normally followed by a thermal anneal at 1000°C for thirty minutes. But temperatures above about 600°C can cause damaged contacts (spiking) and damage to metal layers in a device. Temperatures exceeding about 800°C can cause diffusion of dopants affecting transistor threshold and leakage values. Since the final implant occurs after all frontside device fabrication, the anneal temperature is restricted to 400°C. At this temperature, boron doses of approximately 10^{13} ions/cm^2 have only 10 to 20% of the dopants activated [1]. As the implant dosage increases, the silicon crystal becomes more damaged and the percentage activation decreases. The consequence is that frequency response is affected and dark current can rise to objectionable levels (see discussion below). Therefore, with the standard processing scheme, there is a tradeoff between improving spectral response and improving dark current.

Dark Current:

High performance low light detecting CCDs are also susceptible to dark current, i.e. the thermally generated charge carriers under zero illumination. Excessive dark current will destroy the dynamic range of the imager thereby masking low light level signals. In addition, variations across the array will degrade image quality and can be misinterpreted by subsequent signal processing circuitry. Dark current effects in CCDs range from individual pixels with excessive dark current to high average dark current and variations in dark current across the imaging array. While dark current is normally associated with front side circuitry, crystalline damage arising from unannealed implanted dopants can lead to generation sites for dark current. Therefore, fabrication techniques to improve both the spectral response and dark current of CCDs is highly desirable.

EXPERIMENTAL

CCD Test Vehicle:

Backside-illuminated CCDs containing a 90 pixel x 90 pixel array were used as test vehicles for the laser process. The CCD was a conventional 4-phase buried channel device. In addition to the dark current and spectral response reported in this paper, the CCDs were fully tested for functionality before and after laser processing to ensure no damage to the either the imaging area or the associated electronics.

Excimer Laser Processing Apparatus:

Figure 1 schematically shows the laser processing system. The excimer laser beam is directed into an optical path which homogenizes and shapes the intensity profile to provide uniform illumination across the active area of the CCD without scanning the beam. This is required since the intensity profile emitted by the excimer laser exhibits both spatial and temporal (pulse-to-pulse) nonuniformities and must be correctly shaped for the specific CCD array geometry. A typical intensity profile emitted by an excimer laser is shown in Figure 2 (A). A subsequent shaped and homogenized intensity profile which is directed into a processing chamber and then onto the CCD to be processed is shown in Figure 2 (B). The laser processing system in Figure 1 includes in-situ characterization of the laser process using a reflectivity monitor to measure the melt duration of the silicon material which is an important process control parameter. Additional process controls may include mass flow controllers for process and purge gases, evacuation systems and alignment systems. Details of these subsystems have been described elsewhere [2].

Excimer Laser Process Recipe:

The device physics dictates that high concentration of p^+ dopants be used to prevent the trapping of photogenerated charges near the back surface of the CCD as described above. Therefore, the CCDs were ion implanted with boron to doses of 5×10^{13} cm^{-2}. Rather than receiving a 30 minute anneal at 400°C in a furnace as prescribed in the conventional fabrication for the backside implant, the devices were subsequently transferred to the laser processing chamber and the ambient evacuated and backfilled with an inert gas. Processing was conducted using the excimer laser operating at 248 nm with a KrF gain medium. Pulse repetition rates up to 100 Hz were attainable with pulse energies up to 750 mJ. The laser intensity profile was homogenized, shaped and directed normal to the sample surface. Upon illumination with sufficient laser fluence ($\phi_{melt} \geq 0.7$ J/cm^2), the silicon melts allowing redistribution of the dopants within tens of nanoseconds. The silicon then recrystallizes, resulting in dopants in electrically active sites and annealing of crystalline damage caused by the ion implantation. Processing parameters along with typical and ranges of values are given in Table I.

TABLE I. **Processing Parameters**

PARAMETER	TYPICAL VALUE	RANGE
implant dose	5×10^{13} ions/cm^2	1×10^{13} - 1×10^{15} ions/cm^2
implant species	boron	B, BF$_2$ or none (see alternate process in text)
implant depth	120 nm	5 - 150 nm
furnace anneal	none	≤ 400°C, 30 min
process ambient	helium	inert or dopant gases (see alternate process in text)
sample temperature	23°C	< 400 °C (restricted by the device not the laser process)
laser fluence	1.0 J/cm^2	0.7 - 2.0 J/cm^2
laser wavelength	248 nm	157 - 351 nm
laser intensity profile	tophat, < 5% nonuniformity	< 10% nonuniformity
laser temporal profile	23 ns	10 - 30 ns
number of laser pulses	10	1 - 10

Note, an alternative process involves the elimination of the ion implantation step altogether. In such a case, the process ambient is a dopant gas such as boron trifluoride (BF$_3$), which can be photolytically or pyrolytically decomposed by the laser and incorporated into the molten silicon. Subsequent laser annealing in an inert ambient follows, as above. This in-situ laser doping process is described in more detail elsewhere [3].

RESULTS

Figure 3 shows the electrically active charge carrier profiles of dopant concentration vs. depth obtained using the spreading resistance profiling technique for three individual samples which were all treated in the manner listed in Table I, except for variations in laser fluence. The silicon samples were identical to those used in the fabrication of the CCD arrays. The samples were irradiated with ten pulses with laser fluences of 0.7, 0.8 and 0.9 J/cm^2, respectively. Samples undergoing conventional furnace annealing used for the backside implant showed approximately 10 to 20% boron activation while the laser activated samples shown here exhibit approximately 100% activation. As shown in Figure 3, the dopant profile may be controlled by changes in laser fluence since the depth of active dopant distribution increases with increasing laser pulse energy. Similarly, varying the number of laser pulses can change the profile from a graded profile with peak concentration near the surface to that of a uniform dopant distribution.

Responsivity Improvements:

Responsivity improvements occur in two areas. First, the responsivity becomes more uniform across the array. This is a product of the uniform illumination and subsequent uniform recrystallization of the backside of the CCD. All samples show an improvement in response uniformity originally degraded by the spatial nonuniformities in the implant. Secondly, the response of the CCD to blue and shorter wavelengths of light is improved by providing for a peak dopant concentration at the back surface to allow for the photons absorbed near the back surface to be collected by the pixel electrodes as described in the background. Tests were performed to detect the observed improvement in responsivity with the laser process. Test CCDs were laser annealed on one half of the array with 10 pulses at 1.5 J/cm^2. The devices were subsequently flood illuminated with blue light (400 nm) and a line scan across the device was measured. Figure 4 shows the spectral response line scan from a representative CCD. Note that on the half of the CCD which received laser processing (the left hand side in Figure 4), the response to the blue light improved over that half which received no laser processing (43.4 nA/μW vs. 37.8 nA/μW). The 20% increase demonstrated here is not optimized, but is representative of the improvement obtained using this technique. Additional improvements can be obtained using lower laser fluences and the in-situ laser doping process mentioned above to create a more shallow anneal thereby keeping the peak dopant concentration closer to the surface.

Dark Current Improvements:

CCDs were fabricated and tested. Devices were selected which exhibited dark current defects, i.e. excessive average dark current, nonuniformities, and/or individual pixels with excessive dark current. The test devices were then laser processed in accordance with the recipe in Table I and retested. Results of a typical (not best case) laser annealed sample will be discussed and is shown in Figure 5. This sample was chosen due to the unique spiral defect structure which was "repaired" by laser processing. Figure 5A shows a map of the dark current for the 90 x 90 pixel array prior to laser processing. Numerous defective pixels, with dark currents exceeding 11 nA/cm^2 are present. Figure 5B shows the dark current map following the laser process. Note that all defective pixels were improved. The mean dark current of the 8100 pixels in the array decreased from 9.958 nA/cm^2 to 9.658 nA/cm^2. The standard deviation of the dark current, which is representative of the uniformity in the array, decreased from 4.826 nA/cm^2 to 0.812 nA/cm^2. Furthermore, individual pixels with excessive dark current, attributed to generation at crystalline defects were eliminated or reduced. Table II shows a summary of a correlation of the pixel data before and after laser processing demonstrating that defective pixels with a severe dark current level (> 50 nA/cm^2) are reduced to low or moderate dark current levels. Those defective pixels with low or moderately high dark current levels (< 50 nA/cm^2) are removed completely.

TABLE II. CCD Pixel Dark Current

DARK CURRENT	DEFECT TYPE	NUMBER OF PIXELS	
		PRE-LASER PROCESSING	POST-LASER PROCESSING
0 - 5 nA/cm^2 above array mean	none	7974	8098
5 - 10 nA/cm^2 above array mean	low	66	1
10 - 50 nA/cm^2 above array mean	moderate	46	1
≥ 50 nA/cm^2 above array mean	severe	14	0

CONCLUSION

An excimer laser has been used to activate the final boron implant on the backside of backside-illuminated CCD arrays. Results indicate that the laser fully activates the dopant resulting in a significant reduction in the mean dark current, improved dark current uniformity and repair of defective pixels with excessive dark current. Furthermore, responsivity improvements occur both in the uniformity and the sensitivity (quantum efficiency) to short wavelength (blue and UV) light. Apparent minor modifications in processing techniques in semiconductor fabrication can lead to major cost savings, yield and reliability improvements due to the large volume production and repetitive nature of processing. Therefore, extensive effort is placed on eliminating even one step from a process flow since each step has an associated yield. This is more important involving backside processing of CCDs since substantial fabrication costs and time are invested in the device by this step in the fabrication. Therefore, it is apparent that the laser process described for repair of defected pixels in addition to improving dark current and enhancing blue response simultaneously in one process step is highly desirable alternative to conventional processing. In addition, the laser process described herein is compatible with other laser techniques, e.g. backside thinning (etching) or sidewall texturing which may be implemented in prior processing steps [2,4,5].

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REFERENCES

1. H. Ryssel, I. Ruge, *Ion Implantation*, (New York, John Wiley & Sons, 1986), page 248.

2. S. D. Russell, D. A. Sexton, "Excimer Laser Thinning of Backside Illuminated CCDs", NOSC-TD-1697, November 1989.

3. D. A. Sexton, S. D. Russell, R. E. Reedy, E. P. Kelley, "Excimer Laser Dopant Activation of Backside Illuminated CCDs", Navy Case No. 72,219 (patent pending).

4. S. D. Russell, D. A. Sexton, "Responsivity Uniformity Enhancements for Backside-Illuminated Charge-Coupled Devices (BICCDs) by Excimer Laser-Assisted Etching", NOSC-TD-2103, May 1991.

5. These additional laser processes applicable to backside-illuminated CCDs are described in the following pending patents: Navy Case No. 71,978, 72,726, 73,014, 74,142, 74,182, and 74,183. Information may be obtained by writing to the Patent Counsel, Code 0012 at NCCOSC, RDT&E Division , San Diego, CA, 92152-5000.

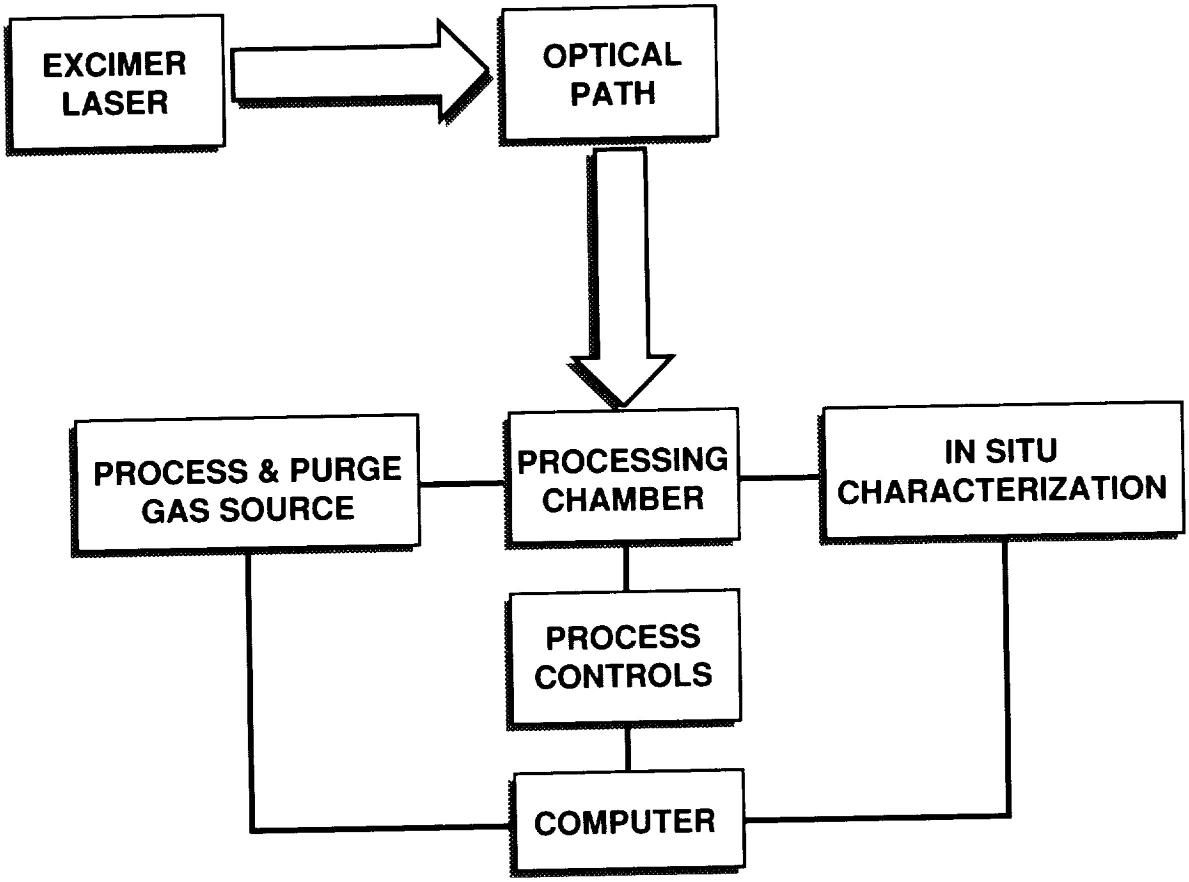
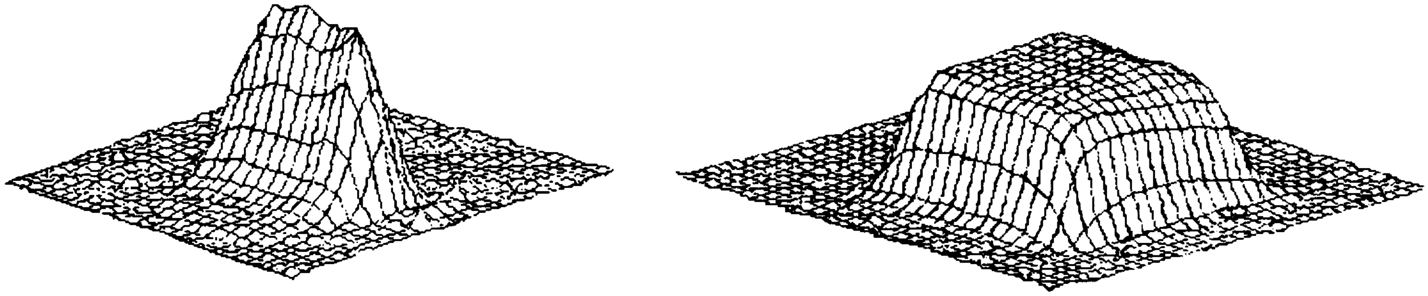


Figure 1. Schematic of excimer laser processing system.



(a) Typical excimer laser intensity profile.

(b) Homogenized intensity profile.

Figure 2.

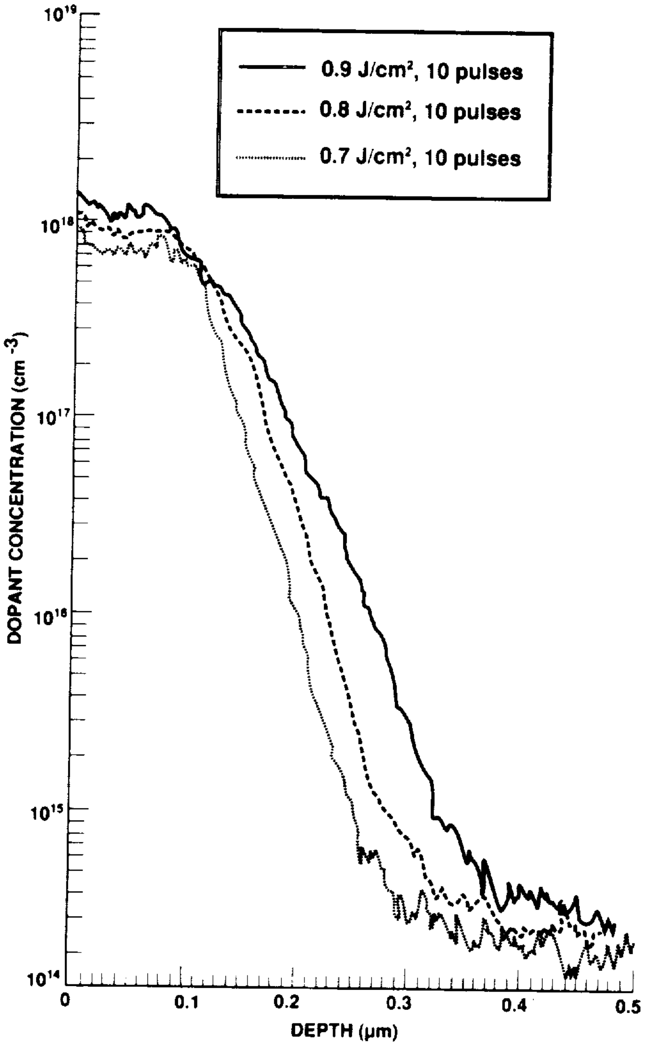


Figure 3. Dopant concentration vs. laser fluence.

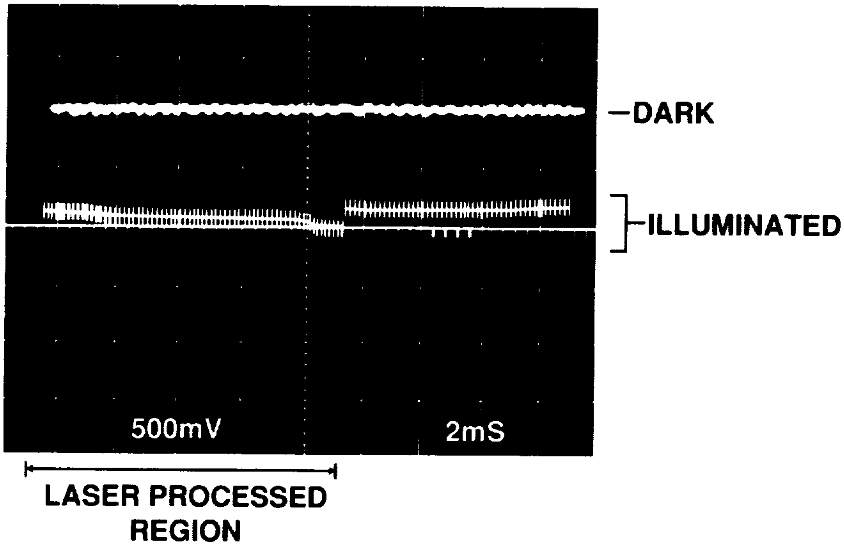


Figure 4. Spectral response line scan.

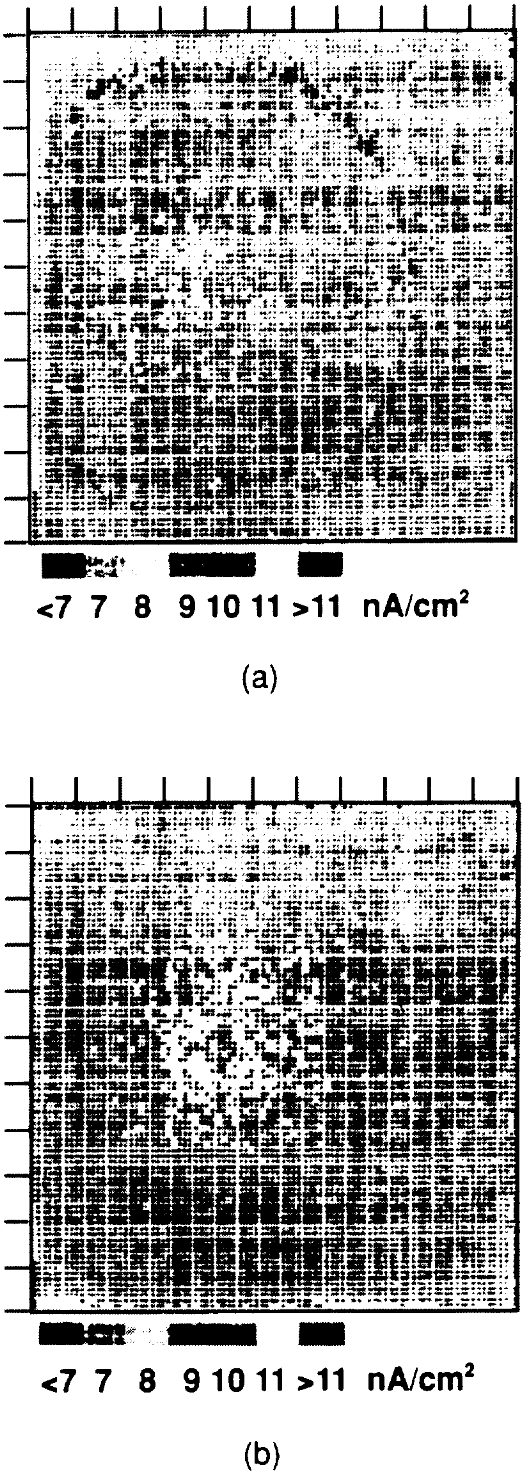


Figure 5. Dark current map (a) before, and (b) after laser processing.