

NEW DEVELOPMENTS IN CCD TECHNOLOGY FOR THE UV-EUV SPECTRAL RANGE

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ABSTRACT: Lately, Charge Coupled Device (CCD) detectors have had great advances both in the visible and in the X-ray spectral range. However, the technology applied to these devices in the ultraviolet (UV) spectral region has not developed as well, because of some problems connected with the interaction between UV radiation and the materials typically used in semiconductor technology. In our laboratory the ultraviolet response of some UV-enhanced CCDs has been investigated. In particular, the quantum efficiency of coronene and lumigen coated and of back-illuminated ion implanted CCDs have been measured in the 304 - 11000 Å spectral range. Very interesting results have been found, mainly for a one ion implanted CCD with quantum efficiency values of more than 60% at 304 Å. Some measurements of the response uniformity of this spectral region have also been made. The results obtained encourage the possible use of these detectors in ultraviolet astronomy with very good performance.

1. INTRODUCTION

Charge Coupled Devices (CCDs) are widely used as imaging detectors both in the optical and in the X-ray spectral range. In many observatories various CCD cameras are operated in the optical. There are very good results in laboratories such as JPL (Janesick et al. 1989, 1990) and Lockheed Palo Alto Research (Stern et al. 1986) in the USA, and Space Research at Utrecht (Verhoeve et al. 1991, Bailey et al. 1990) and Leicester University (McCarthy and Wells 1992) in Europe. The use of these devices in the ultraviolet (UV) spectral region is obviously very attractive especially for space instruments. But, CCD technology in this spectral region presents some problems connected with the interaction between UV radiation and silicon. As shown in Fig. 1 the absorption depth in the 1000 - 4000 Å region is very low and then the interaction occurs on the first layers of the material. For example, the relatively thick gate oxide layer (500 - 1200 Å) on the CCD front face strongly absorbs UV radiation, thus it is impossible to use front-illuminated CCDs for direct detection of UV radiation.

Many solutions have been tried: the most common technique is to sublimate a phosphor under vacuum conditions, such as "lumigen" on the sensitive surface (Bredthauer et al. 1988). This is done both for front-illuminated and thinned back-illuminated CCDs, down-converting the UV radiation and the absorption due to the thick polysilicon gate can be avoided. In back-illuminated CCDs, other problems have to be solved. After the device is thinned, a "native" back-oxide layer forms naturally which contains a lot of "dangling bonds" creating surface states. Since there are positive charges associated with them, a depletion region at the back of the CCD forms (backside well) and, as stated before, owing to the extremely short path length (< 100 Å) in silicon for UV photons, the charge is photogenerated very near to the CCD backside, so that the recombination is highly probable and a lot of signal charge can be lost.

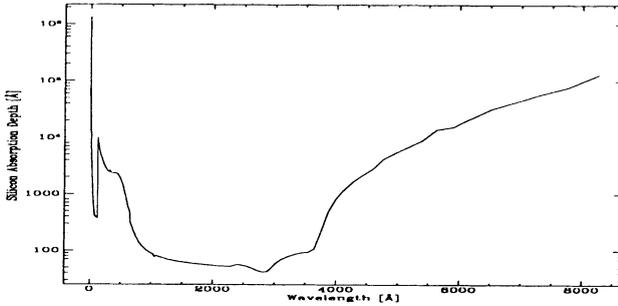


Fig. 1. Silicon Absorption Depth vs wavelength in the 1.2 - 8500 Å region.

Some methods have been developed to reduce surface state problems using different “back-accumulation” techniques. They are based on the hypothesis that the back surface potential can be *pinned* by heavily populating it with holes which create an electric field that directs the photogenerated charges away from the back surface (Janesick et al. 1989). The methods can be divided into three categories: backside charging or UV flooding (Janesick et al. 1985), flash gate techniques (Janesick et al. 1989) and ion-implantation and successive laser-annealing.

The last technique is based on the fact that the effect of a p^+ implantation on the backside lowers the backside well width (Janesick et al. 1985) to values of the order of 10 Å or less. Moreover, the implantation damages the crystal lattice sites, so that it is necessary to anneal and reconstruct the crystal structure. To do this a pulsed laser annealing of the CCD back surface is adopted (Bailey et al. 1990); if the process is optimal, at the end, no significant residual backside well should be present.

There is only one small problem that can be still present: if some ions penetrate deeply into the surface they cannot be reached by annealing; in such a way, the associated crystal damage acts like traps for the charge signal, reducing the QE performances. Thus, to minimize this problem, a low energy ion-implantation technique must be used.

Another new technique named “*anodic etching*” has been developed by English Electric Valve (EEV) and it consists in the removal of the oxide layer by selective *etching*. This technique allows the boron-implanted layer to be thinned in a controlled way (by means of an appropriate voltage during the anodization). Anodic etching could be applied either before or after laser annealing. Thus the deep penetrated boron atoms, which are left unannealed in the standard technique, could be reached now. Another technique that is under investigation at EEV is the *ultra low energy boron implantation* ($E < 2$ KeV) that leaves no unannealed boron and can be combined with “*anodic etching*”.

In the following sections, I will describe the results obtained from measurements of the QE and uniformity response performances in the 300 - 11000 Å spectral range of some UV-enhanced EEV CCDs. I selected one per type: one is front-illuminated and phosphor coated, the others are thinned back-illuminated with the surface treated as: phosphor coated, ion-implanted and ion-implanted with the “*anodic etching*”.

2. CCD CHIPS

We have tested several EEV CCDs of the CCD02-06 (385 x 576 pixels, 22 μm pixel size) series. Table 1 summarizes the relevant characteristics of the four selected CCDs.

TABLE 1
Characteristics of Four Selected CCDs

CCD TYPE	ILL.	SURFACE TREATMENT	NOTES
Thick	Front	Lumigen vacuum sublimation	scientific grade
Thinned	Back	Coronene coating	scientific grade
Thinned	Back	Ion-implanted laser annealed	E = 10 KeV, C. = 10^{15} cm^2
Thinned	Back	Ion-implanted laser annealed	as above, anodic etched

The back-illuminated ion-implanted CCDs are of the same type as those furnished by EEV for the characterization tests of the detector for the Reflection Grating Spectrometer on the XMM mission (Verhoeve et al. 1992); the only difference is that this CCD has a lower resistivity (20 ohm x cm instead of 1500 ohm x cm). To achieve the optimal p^+ layer distribution, the energy of the implanted ions was only 10 KeV, the concentration was $10^{14} - 10^{15} \text{ cm}^{-2}$ and the implanted angle of incidence was increased with respect to the typical angle of 7° . to avoid channeling of implanted boron to great depth: in such a way, the peak of the ion distribution should be, theoretically, at only about 0.05 μm inside the CCD. It is important to note that in the last CCD, EEV has applied the “*anodic etching*” after laser annealing. At a scan time of 100 μs per pixel all the CCDs show a readout noise smaller than 10 electrons rms.

3. EXPERIMENTAL SYSTEM

To evaluate the CCDs performances in the 300 - 11000 \AA region, two different test facilities have been used. One performs QE measurements in the 300 - 2500 \AA range and is located in Padua (Department of Electronics and Informatics) (Bonanno et al. 1992, Naletto et al. 1992) and the other is located in Catania (in our Observatory) and can characterize cooled CCDs in the 1150-11000 \AA range. In these laboratories measurements of the response uniformity are also possible (REFERENCES 2) [11,12]XXXX

The vacuum facility used for the EUV spectral range measurements is shown schematically in Fig. 2: it consists essentially in a normal incidence monochromator and a calibration chamber.

The monochromator has a Johnson-Onaka configuration with an f/10 aperture and a toroidal reflection grating (600 l/mm, Pt coated). The entrance and exit slit are fixed and are 100 μm wide and three mm long. It is pumped by a turbomolecular pump which allows it to

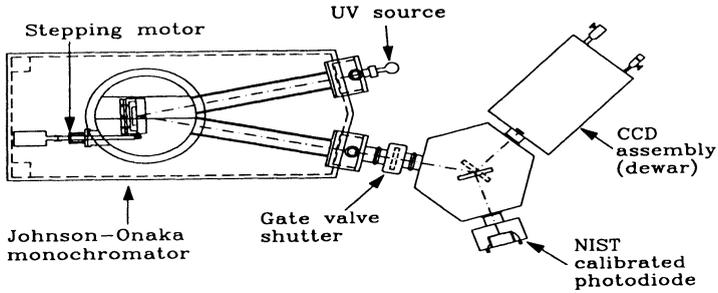


Fig. 2. Scheme of the calibration facility used for the QE evaluation in the EUV.

reach a pressure of about 2×10^{-6} mbar. As sources, both a 30 Watt Hamamatsu Deuterium lamp sealed with a MgF2 window emitting in the 1150 - 2500 Å spectral range and an open hollow cathode lamp to cover the range down to 300 Å have been used. The lines used are 304 Å (He II), 461 Å (Ne II), 584 Å (He I), 735 Å (Ne I) and 920 Å (Ar I). The calibration chamber accommodates a rotating Pt coated toroidal mirror mounted at its center which can focus the monochromatized beam on two symmetric positions, where both the CCD and the calibrated photodiode are mounted. To evaluate the QE, a pair of NIST calibrated photodiodes have been used: one sealed for the 1164-2537 Å range and the other windowless working in the 50-1216 Å region.

The system used for the 1150 - 11000 Å spectral range measurements is shown schematically in Fig. 3: it is based essentially in a precision 0.39-meter focal length vacuum monochromator. This last, thanks to a triple grating turret that can accommodate gratings blazed at appropriate wavelengths, allows good and automated measurements in the above mentioned operating range. Some off-axis paraboloidal mirrors are used to focus the beam on the monochromator. As sources, we use a Tungsten lamp to cover the 4000 - 11000 Å region and a 150 Watt Deuterium lamp sealed with a MgF2 window emitting in the 1150 - 3000 Å spectral range. To cover the 3000 - 4000 Å range, we actually use some spectral lamps, but in the future a Xenon lamp will be used. A movable plane mirror selects the source. To evaluate the QE of the CCDs in the spectral range of interest, three NIST calibrated photodiodes have been used: one sealed with a MgF2 window for the 1164 - 2537 Å range and the others, a quartz window working in the 2000 - 11000 Å region.

Actually, we use the system assembled on an optical bench without the vacuum chamber reducing the operating wavelength range to 2000 - 11000 Å. The system configuration allows simultaneous measurements to be made on both detector and calibrated photodiode, reducing the errors due to the source variability during the measurements.

The CCD controller used for these measurements has been made in our laboratory (Bonanno and Di Benedetto 1990) and in the future we will use the one designed for the Italian National Telescope "Galileo" (see Bonanno (1995) for the essential characteristics). The acquired images are analyzed using two packages, IDL and IRAF running in Unix-machine workstations.

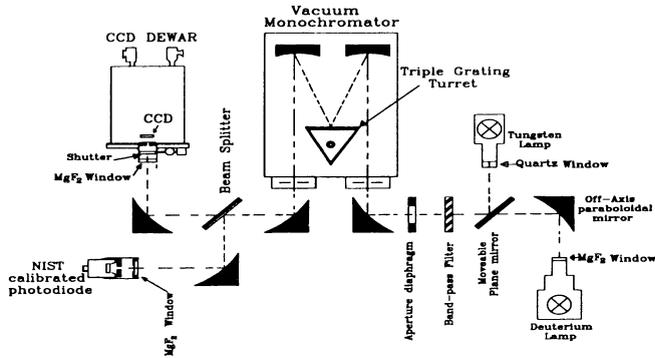


Fig. 3. Scheme of the calibration facility used for the QE evaluation in the 1150 - 11000 Å spectral range. The system is mounted on an optical bench and is presently used for the 2000 - 11000 Å spectral range because the optical components are not housed in a vacuum chamber.

4. QUANTUM EFFICIENCY MEASUREMENTS

The QE measurement is conceptually easy: it is necessary to compare the CCD signal (electrons) with the signal measured by a calibrated photodiode at each wavelength. But the real measurement is not so simple, particularly at wavelengths shorter than 2000 Å. Since the sources and their characteristics are different for the regions above and below 1200 Å, different methods of evaluating the QE are adopted for the various cases in the two laboratories (Bonnano et al. 1992, Naletto et al. 1992). Particular care has been taken in the evaluation of the CCD conversion factor F , expressed in e^-/DN , because the accuracy of this parameter influences all data. It must be pointed out that in the UV spectral region the QE of CCDs is defined as the product of the effective CCD QE; that is, the fraction of incident photons producing one or more e^-h pairs that are collected in the CCD pixel wells, multiplied by the so called electron yield; that is, the number of e^-h pairs produced per interacting photon (usually it is assumed that the e^-h pairs are generated by an energy of 3.65 eV).

4.1 300 - 2500 Å Spectral Range

The results of the QE measurements in the 300 - 2500 Å region are shown in Fig. 4 and refer to data acquired about one hour after the cooling of the CCDs.

The measured QEs of both front-illuminated and back-illuminated coated CCDs, have a similar behavior. They show values greater than 10% at longer wavelengths and a minimum of the order of 1 - 1.5% in the 700 - 1200 Å range, and both show an increase at the shortest wavelength. A different behavior can be noted on the two ion-implanted devices: first of all, they show a QE greater than 10% in a larger spectral range (900 - 2500 Å), at wavelengths shorter than 700 Å the QE increases quickly and in particular, the "etched" one has a QE greater than 60% at 304 Å. A difference of 25% can be noted between the two ion-implanted CCDs in the 400 - 2000 Å that drops to 10% at longer wavelengths. Moreover, it is very interesting to observe that the two QE curves converge in the UV region: this fact agrees fairly

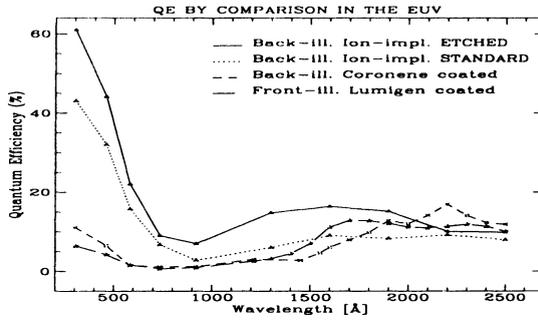


Fig. 4. Comparison between the quantum efficiency data for the various CCDs in the 300 - 2500 Å spectral range.

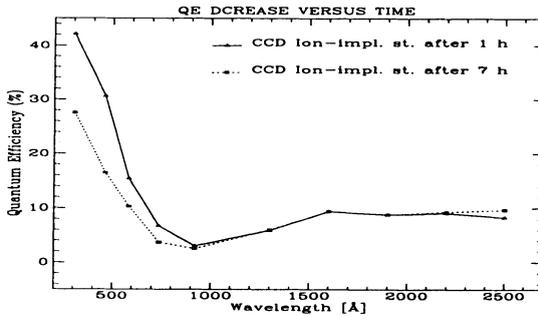


Fig. 5. Quantum efficiency decrease vs time for the thinned back-illuminated ion-implanted "standard" in the 300 - 2500 Å spectral range.

well with the QE measures obtained in the range 2500 - 11000 Å (see Fig. 6). The minimum values are showed in the range between 700 Å and 1200 Å and are 10% for the "etched" and 7% for the "standard".

During the QE measurements, a rather interesting phenomenon has been observed. In practice, the QE decreases in time when the CCDs are cooled, to restart at high values after a cooling cycle. In Fig. 5 the QE data, taken at different times after the cooling of the CCD thinned back-illuminated ion-implanted "standard", is shown. After seven hours the QE at 584 Å from 15% drops to 10%.

Some tests were made to find whether this decrease was connected with the UV illumination or if it is due to other effects. There is only one obvious conclusion: the QE decrease in time is mainly related to the non perfect vacuum conditions. In fact the CCD, when cooled, acts as a cryo-pump and some contaminants present in the vacuum chamber are frozen over the CCD.

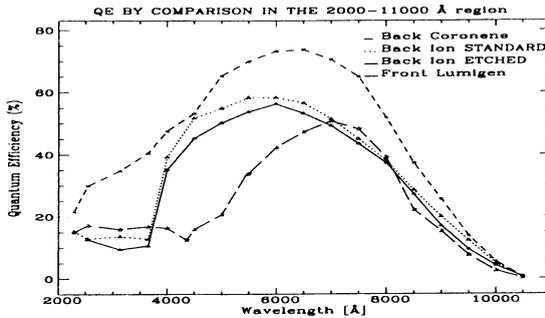


Fig. 6. Comparison between the quantum efficiency data for the various CCDs in the 2000 - 11000 Å spectral range.

4.2 2000-11000 Å Spectral Range

The results of the QE measurements in the 2000 - 11000 Å region are compared in Fig. 6. For the sake of clarity, we decided not to show the error bars, which are at most not greater than 10% in the UV region, and much lower at the other wavelengths.

In the 4000 - 10000 Å range all the CCDs, either front- or back-illuminated, show a “typical” QE. In contrast, in the 2000 - 4000 Å range we note a different behavior for the various CCDs. The QE of the *front lumigen* CCD is higher than 15% and is almost constant in that spectral range. The *back coronene coated* CCD shows a higher QE. But, I have to point out that, unfortunately, the QE decreases with the number of times the CCD is operated. The two curves of the *back ion* CCDs are slightly shifted within a 10% difference, and, being both within their error bars, we can conclude that they are comparable. Thus, from these results we can say that the “*anodic etching*” technique improves the QE mainly in the EUV spectral region, leaving it practically unchanged at longer wavelengths.

5. UNIFORMITY MEASUREMENTS

To study the uniformity of the CCDs response and its color dependence we used a system constituted essentially by an integrating sphere that is illuminated through interferential filters by different sources in the 2000 - 11000 Å range. Instead, in the 300 - 2500 Å range, a ground glass inclined at 45° to collect the diffuse radiation of the beam coming out from the monochromator is inserted in the calibration chamber. To be sure of the validity of this method, we have been checked that the fluorescent contribution to diffuse light due to the ground glass is negligible with respect to that of the UV.

Here we report the analysis at only two UV wavelengths: $\lambda = 1600 \text{ Å}$ and $\lambda = 2200 \text{ Å}$ for the front-illuminated CCD and the back-illuminated ion-implanted “standard” CCD. The pixel to pixel variations have been estimated by dividing the CCD areas into 10×10 pixel sub-areas (to minimize the large-scale variations due to the source), and evaluating the mean signal

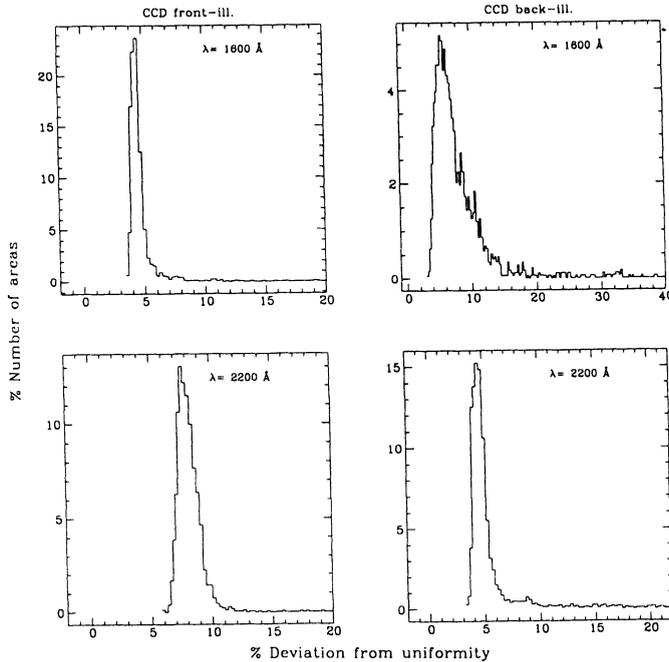


Fig. 7. Deviation of uniformity at $\lambda = 1600 \text{ \AA}$ and $\lambda = 2200 \text{ \AA}$ for the front-illuminated CCD and the back-illuminated ion-implanted “standard” CCD.

m and the standard deviation σ for each sub-area. The deviation from uniformity in any sub-area is given by the ratio $2\sigma/m$.

Fig. 7 shows the histograms relating the number of the sub-areas to their deviation from uniformity. As can be noted, the front-illuminated CCD shows an opposite behavior with respect to the back-illuminated ion-implanted “standard” CCD. While at $\lambda = 1600 \text{ \AA}$ almost the totality of the considered subareas of the front-illuminated CCD have a narrow distribution around 5% of non-uniformity, at $\lambda = 2200 \text{ \AA}$ the distribution is enlarged and around 8% of uniformity. Exactly the contrary is observed for the back-illuminated ion-implanted “standard” CCD. This is mainly due to the absorption depth of the materials at these wavelengths.

6. CONCLUSIONS

The QE measurements of the selected CCDs show that both the techniques of coating the CCD surface with some scintillators and of ion-implantation followed by laser annealing are effective in having a rather good QE in the UV spectral region.

The coated CCDs have shown a reasonable QE in the region in which the scintillator efficiently converts the UV radiation, while at shorter wavelengths they show a rather poor QE. Furthermore the QE depends on the number of times the CCD is operated.

The ion-implanted CCD has shown a very high QE, especially at the shortest wavelengths, and a uniformity of response which is good at longer wavelengths; this was an unexpected

result, so other measurements have to be done to better understand it. The *etching* process is used to increase the EUV sensitivity of thinned back-illuminated and ion-implanted CCDs. In particular, since QE values as high as 70% have been measured at the shortest wavelengths, taking into account also the electron yield and the very low noise shown by currently available devices, it is possible to assert that in the spectral range below approximately 600 Å these detectors can work practically in a near photon-counting regime.

The problem of the QE decrease with time, due to residual contaminants inside the vacuum chamber, still remains, but it can be strongly reduced by improving the vacuum and by operating the devices at higher temperatures permitted by new devices that can operate in "inverted mode". In fact Multi Pinned Phase (MPP) devices do not need to be cooled to very low temperatures, thus avoiding the condensation of the contaminants over the sensitive surface. A more accurate evaluation of the QE of MPP CCDs in the EUV will be done in the future.

In conclusion, the results obtained show the real possibility of adopting in the near future these devices as optimal image sensors in the UV and EUV spectral range. In this respect, an effort is already in progress, both as regards the development of new CCD manufacturing technologies by EEV, and the improvement in the test facilities available in our laboratories.

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DISCUSSION

STOVER: At Lick we are investigating two additional techniques to address the problems of backside treatments. First, we are having wafers fabricated which have the highly doped boron layer built into the silicon. This makes thinning the CCD easier. In addition, it should provide backside accumulation properties similar to ion implanting with annealing. Second, we are planning to experiment with n-type CCDs. CCDs made with this type of material will not have the backside accumulation problems of standard CCDs.

BONANNO: Very well. I agree completely to experiment with n-type CCDs. I hope we will see the results of these processes in the future.

COHEN: Since no one from JPL appears to be here, I should like to point out that Paula Grunthner of the Microdevices Lab is working on this problem and is using a different technique. This has some advantages and some disadvantages - the process requires very high vacuum and cleanliness and is inconsistent with most commercial production. But the QE waves are spectacular. Paula expects to distribute a few CCDs treated in this way for testing soon.

BONANNO: OK. I will read in the future the results of the QE measurements.

JORDEN: On the graph showing QE of the four CCDs over the 2000-10000 Å range - why does the coronene coated thin device show such a high peak (600 nm) response of 80% (relative to 60% on other thin ones)?

BONANNO: I think that the coating acts as an antireflection coating at these wavelengths.

CULLUM: I am not clear on your reference to ESO-type coronene coatings. ESO has not used coronene coatings, only laser dye coatings on an acrylic base. Could you clarify what these coatings consist of?

BONANNO: EEV said that the coating applied on the thinned back illuminated CCD is coronene and the method utilized is similar to the one used from ESO. This is an older technique that is very different from the phosphor sublimation under vacuum conditions.