VIDEO SIGNAL SENSITIVITY IN CHARGE COUPLED DEVICES WITH TEMPERATURE VARIATION

Vishal Sakarvadiya[1], Parul Singh[2], Rafik Saiyed[3], Arup Banerjee[4]
Space Applications Centre, Indian Space Research Organization (ISRO), Ahmedabad-380015
E-mail: [1]vishals@sac.isro.gov.in, [2]parulsingh@sac.isro.gov.in, [3]rafik@sac.isro.gov.in, [4]arup_b@sac.isro.gov.in

KEY WORDS: absorption, QE, temperature sensitivity, BSI

ABSTRACT:
Si based Charge coupled devices (CCD) are fabricated on two technologies, front illuminated and back illuminated. Technology selection is done based on responsivity requirement in wavelength region of interest. This paper discusses detector response sensitivity with respect to temperature variation depending on selected technology. In back side illuminated (BSI) detectors, photons are directly impinged on the active epitaxial layer. Depth of absorption (DoA) vary depending on wavelength of radiation. Shorter wavelength (B1:450nm-520nm) is absorbed near the surface of exposure to EM radiation of epitaxial layer. Longer wavelength (B4:770nm-860nm) get absorbed deeper into the Epi layer towards the buried channel. DoA is a function of wavelength and temperature and it decreases with increase in die temperature. The generated free carriers (electrons) are pulled by the electric field under application of gate voltages. Carriers generated by shorter wavelength receives lower field strength. Hence, higher possibility of getting recombined before being pulled by the electric field. With increase in temperature the probability of getting pulled by the electric field decreases further. Hence, some of the carriers may get lost due to recombination. On the contrary, due to high depth of penetration, carriers generated by higher wavelength receives greater field strength and hence, greater probability of detection. Moreover, the field strength is also a function of carrier stored under a gate for a given bias. This is one reason which may lead to signal amplitude dependent spectral band specific sensitivity to temperature variation. Detection probability is usually defined as an electro-optical parameter known as quantum efficiency. So, in these devices, shorter wavelengths show a greater sensitivity to temperature variation compared to longer wavelength.

1. INTRODUCTION:

In CCD, photons are converted into electron-hole pairs in photosensitive region, known as depletion region and then confined by electric field into a pixel defined by gate electrodes. These charges are sequentially readout through shift registers followed by output amplifier. Photons of shorter wavelengths are absorbed near to silicon surface and longer wavelengths travel deep into Si before being absorbed. Typical absorption depth of photons as a function of wavelength at 27°C is shown in Figure 1.

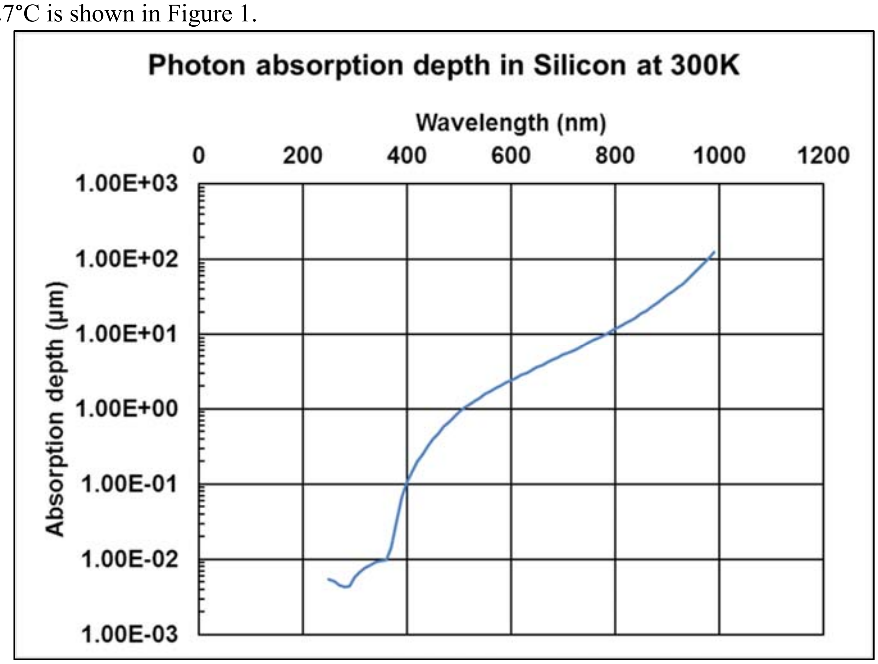

Figure 1: Silicon photon absorption characteristics (James R. Janesick)

In front illuminated CCDs, photon has to travel through polysilicon gate structure and oxide before getting absorbed in photosensitive region. As absorption depth near blue region (around 400nm) is ≈100nm, which is comparable to polysilicon gate thickness (typically around 70nm), hence a significant percentages of photons of near blue region get absorbed in polysilicon gate and do not contribute in electron-hole pair generation. Therefore applications where higher sensitivity (Quantum Efficiency) is required in lower wavelength range i.e. near 400nm backside illuminated CCDs are used.

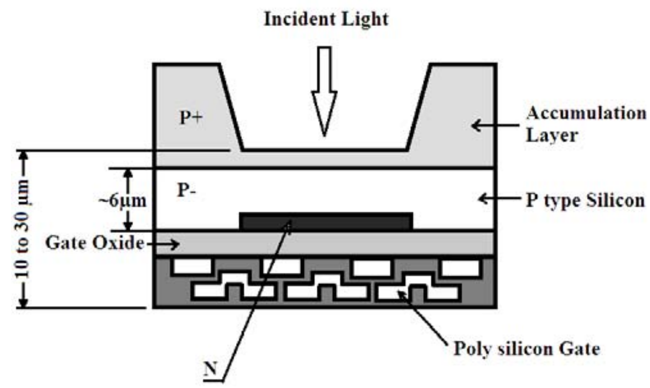

Figure 2: Cross section of back thinned CCD (Hamamatsu Corporation)

Typical back illuminated CCD cross section is give in Figure 2. In BSI CCD bulk silicon substrate is thinned so that lower wavelength photons get absorbed directly into active region and result in higher QE. Comparison of quantum efficiency (QE) enhancement from front to backside illuminated CCD is shown in Figure 3.

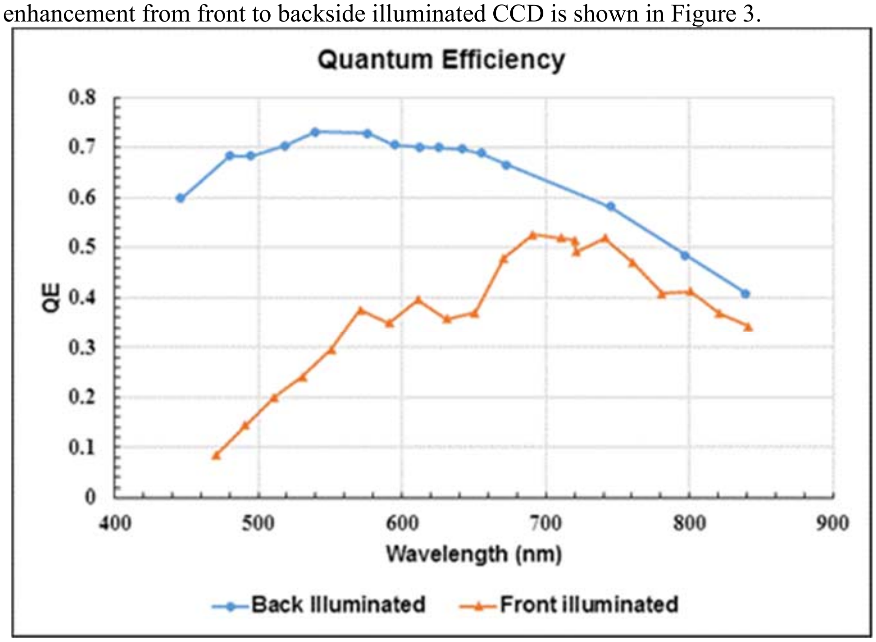

Figure 3: Typical QE measured for front and backside illuminated CCD

2. TEMPERATURE SENSITIVITY:

CCD performance is operating temperature dependent (James R. Janesick). Majorly three parameters are affected by temperature: charge transfer efficiency, dark current and quantum efficiency.

In CCD, charge is transferred due to thermal diffusion, self-induced drift and fringe field effect (James R. Janesick). For transferring small charge packets, thermal diffusion and fringe field plays major role while for large charge packets self-induced drift dominates charge transfer. Charge transfer inefficiency (CTI) when only thermal diffusion applies is given by:

$$CTI = e^{-t/\tau}$$

Where t is transfer time, τ is diffusion drift time constant and define as

$$\tau = \frac{L\ x\ L}{2.5\ D}$$

Where L is gate length in cm and D is diffusion coefficient and define as

$$D = \frac{kT\mu}{q}$$

Where μ is electron mobility, k is Boltzmann constant and q is electronic charge.
Mobility decreases with increasing operating temperature due to lattice scattering of electrons, hence increases CTI.

Second effect is due to exponential increase in thermally excited electron-hole pairs which results in increase in dark current. Dark current normally doubles for each 8-10°C temperature rise.

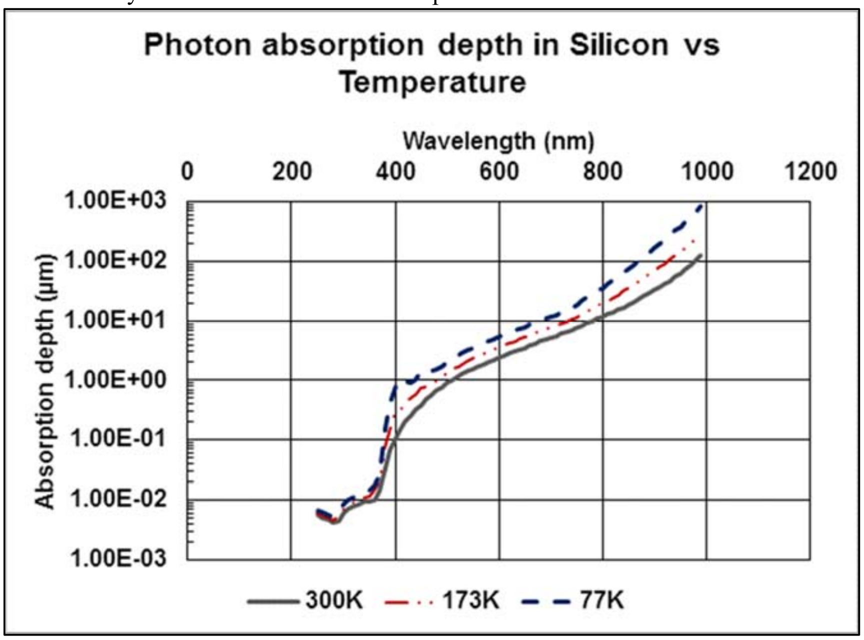

Figure 4: absorption depth as a function of wavelength at different temperatures (A. Ronzhin et al.)

QE is directly related to absorption of photons. As shown in figure 4, photon absorption length is temperature dependent. This happens due to variation in silicon band gap with temperature. variation in the photon absorption leads to change in QE and it affects the output signal of the CCD.

An experiment has been carried out on BSI CCD device to observe the effect of temperature on video signal (Temperature sensitivity). This shall be discussed in following sections.

3. CCD device details and Test setup

The CCD device on which experiment was conducted is a BSI CCD device having standard epitaxial thickness and 17.6μm X 17.6μm pixel size. Full well capacity of the device is 400ke- with typical conversion gain of 6μV/e-. As explained earlier, shorter wavelength photons get absorbed near to surface and higher wavelength photons penetrate deeper before absorption. So in order to enhance QE in blue region, different methodologies are used. For this sensor, internal charging method has been used where a thin P+ implant is done on back surface of sensor. An internal electrical schematic of a sensor with this methodology is shown in figure 5. This creates an electric field which drives electrons to the depletion region for detection.

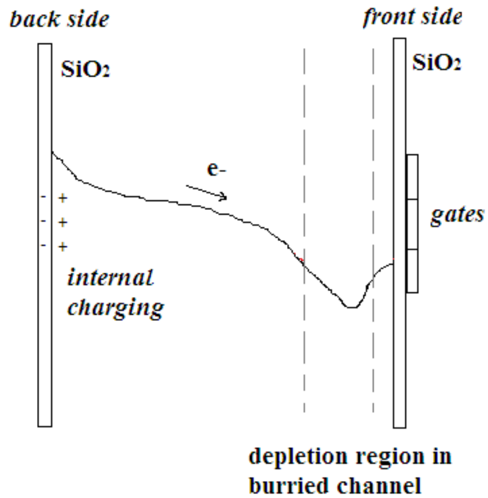

Figure 5: Potential well diagram for BSI buried channel CCD (Michael Lesser, 2015.)

A test setup catering to experimental requirements was established as per block diagram given in figure 6. This test setup consists of CCD sensor drive and video output acquisition electronics, low noise DC power supplies, uniform light source with broadband optical filters and flux meter, temperature control mechanism with cold finger and temperature sensor. As shown in figure, for controlling CCD temperature a copper based cold finger was kept on back surface of CCD which takes the heat from CCD. Liquid based cooling arrangement had been made in order to remove heat load from cold finger and maintain its temperature within ±0.3^{O}C.

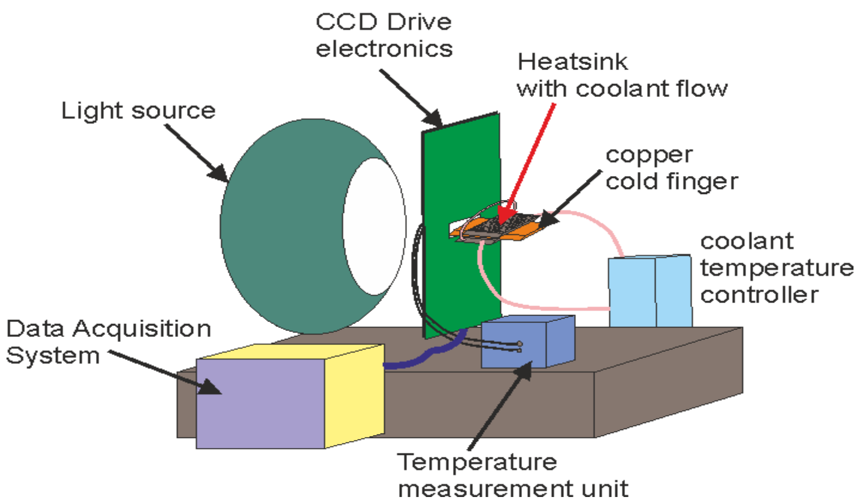

Figure 6: Block Diagram of Test Setup used for experiment

4. EXPERIMENTAL RESULTS:

During experiment, CCD temperature was changed by altering temperature of cold finger. Stability of the temperature was monitored using 6-1/2 digit Digital Multimeter. Studies on temperature dependency of detector sensitivity was carried by varying illumination condition and in different spectral bands. Following sub sections discusses the results.

4.1 Temperature Sensitivity in Different Bands:

To understand band wise variation of sensitivity to temperature, four different optical bands were selected covering VNIR spectral region. These optical bands are (1) B1:450nm-520nm, (2) B2:520nm-590nm, (3) B3:620nm-680nm, and (4) B4:770nm-860nm. Detector response variation with temperature in different bands is shown in figure 7. Illumination condition, in each of these bands, was kept such that the detector response is near to 50% of saturation level.

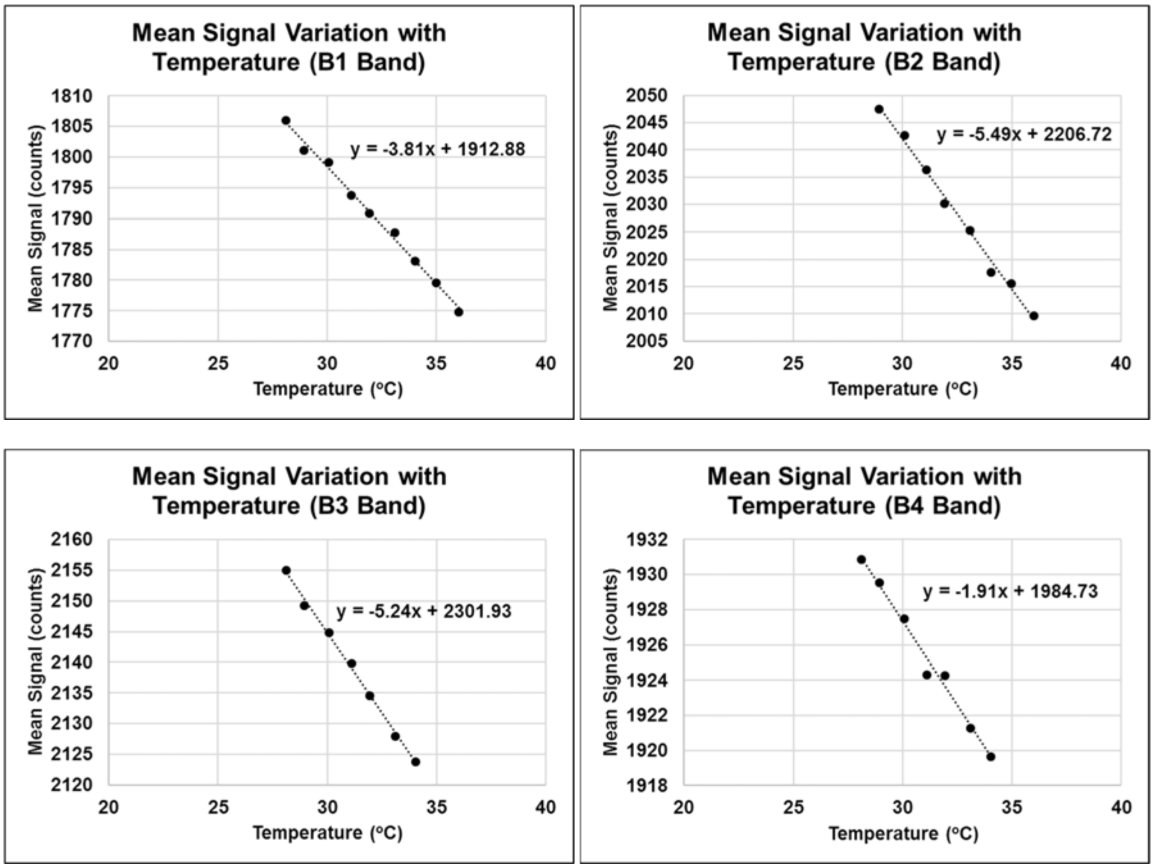

Figure 7: Device signal response variation with temperature in different bands

Based on the results it is observed that the signal response decreases with increase in temperature for all the bands. Figure 9(a) shows variation of temperature sensitivity in different optical bands. Measured quantum efficiency (QE) curve of this CCD device is shown in figure 9(b). From these observations it is evident that band B2 and B3 are more sensitive to temperature variation and B4 is less sensitive.

As photon absorption depth is high in B4 band, photons will be absorbed deeper into the sensor, near the front surface and thus higher charge collection efficiency compared to other bands. With increased temperature, the absorption length decreases but still the photon absorption occurs close to front surface, hence the temperature sensitivity is less in B4 band.

In B2 and B3 band, the photon absorption occurs around depletion region near to maximum potential giving high charge collection efficiency. When absorption length decreases with increased temperature, the photons in these bands will get absorbed away from maximum potential region toward back side surface, leading to significant reduction in signal.

For B1 band, absorption length is very less, therefore photons are absorbed near to back surface, away from depletion region. To increase the signal response, additional P+ implant is done (at the top surface of backthinned structure). Absorption length decreases with increase in temperature, as a result, blue photons are absorbed just inside the surface exposed to input light. Generated carriers are partly drifted by the gate potential, towards electrode, and rest are absorbed in the P+ layer. This effect increases with increase in temperature and thus reducing the signal response.

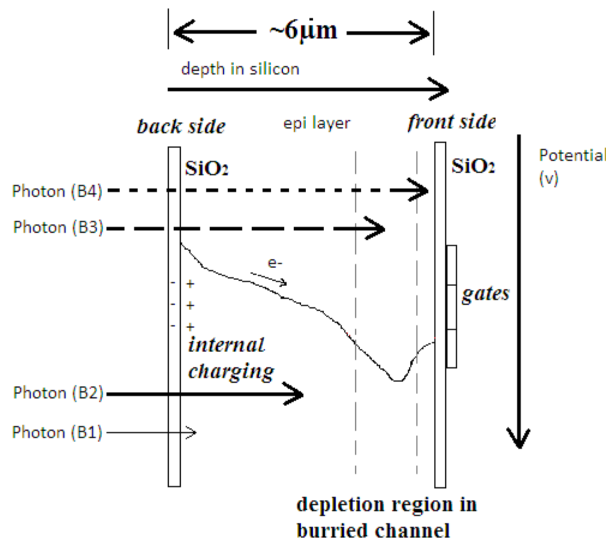

Figure 8: Pictorial view showing absorption length of photons of different wavelength (Michael Lesser, 2015)

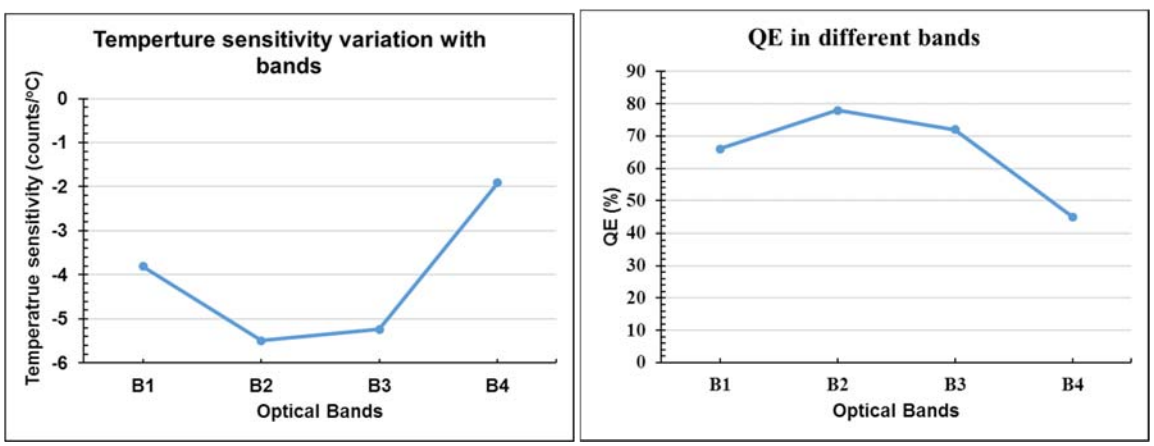

Figure 9: (a) Temperature sensitivity compared in different bands (b) QE of device in different bands

4.2 Temperature Sensitivity at Different Illumination Levels:

In another test condition, the light falling onto the CCD device was changed and variation of temperature sensitivity was measured. Different illumination levels were generated by controlling aperture size of light source and by feeding constant current and voltage to light source lamp. This was necessitated to prevent the change in colour temperature of tungsten halogen lamp, which leads to change in spectrum of the light source.

Measurement at different illumination levels in all four bands was carried out and variation of signal against temperature for each illumination level was plotted and fitted linearly to calculate the temperature sensitivity. Figure 10 shows, temperature sensitivity of device response at different illumination conditions for all the four bands. As shown in Figure 11, with increased charge collection, the potential in depletion region decreases and broadens toward front surface. This reduces the strength of electric field in depletion region and hence the charge collection efficiency. It is observed that in B4 band, effect of illumination is less on device temperature sensitivity. In B4 band, the absorption is near to front surface as shown in Figure 8, so the charge collection efficiency is not much affected even though the field strength is reduced. Lower wavelength photons, which get absorbed away from front surface and near to minimum potential region get affected much with increased illumination.

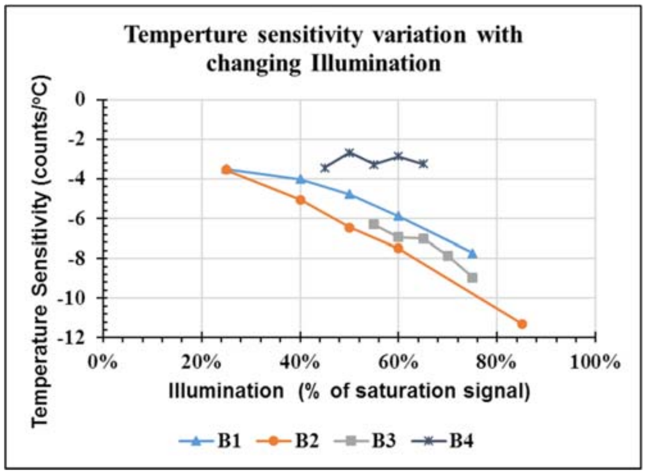

Figure 10: Temperature sensitivity variation with illumination

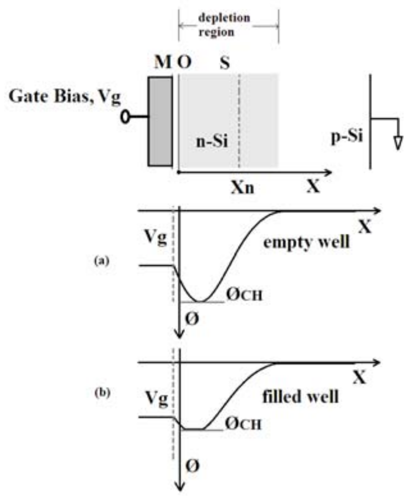

Figure 11: Potential well diagram for empty well and filled well (Albert J. P. Theuwissen)

5. CONCLUSION

Temperature dependency of video signal in BSI CCD has been characterized at different wavelength and different illumination level. Results show that the signal response reduces with increase in temperature. It is observed that in B4 band, the signal has lower sensitivity with temperature variation, compared to other bands. Also in B4 band, the sensitivity with temperature is only marginally affected by variation in illumination level. The temperature sensitivity results can be used to derive the temperature control requirement of the CCD during on-board operation.

6. ACKNOWLEDGEMENT

Authors would like to thank, Director Space Applications Centre, Deputy Director SEDA and Group Director EOSDIG for their guidance and encouragement for this work.

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