

Low Cost Ambient Light Sensing Device based on Sulphided Cu_2O Thin Film Photo-Sensors



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ABSTRACT: A standalone ambient light sensing device was constructed by interfacing a sulphided Cuprous Oxide (Cu_2O) thin film semiconductor based photo-sensor. The photo-sensor was custom fabricated by depositing n-type Cu_2O on a titanium substrate followed by a sulphidation process that formed a $\text{Cu}_2\text{O}/\text{Cu}_x\text{S}$ thin film semiconductor heterojunction. Evaporated gold contacts were placed on top of the film. The photo-sensor was operated in the photovoltaic mode and once interfaced to the device, the sensor photovoltage was further amplified and measured through a 10-bit analog to digital voltage converter embedded in a microcontroller. A liquid crystal display was interfaced to the microcontroller to display measurements. Data logging was done directly to the available microcontroller flash memory or through a RS-232 serial communication link to a PC. The sensor was sensitive to a broad range of intensities (0 – 120,000 lux) with a fast photo-response time on the order of a few hundred milliseconds. The available extra microcontroller ports could be utilized for device control and feedback by interfacing other suitable electronics. The total cost of parts for the device was less than US\$25.

Keywords: Ambient Light Sensing Device, Photo-sensor, Cuprous Oxide Thin Film Semiconductor, Electrochemical Deposition

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1. Introduction

Ambient Intelligence (AmI) is utilized in many modern domestic and industrial electronic systems for the purpose of automation and power consumption optimization [1], [2]. Ambient Light Sensors (ALS) are integral to AmI systems, such as liquid crystal display (LCD) backlight optimization systems [3], adaptive room lighting systems [4], [5], or any other electronic system that rely on light intensity level of the surroundings. Due to a wide range of applications available mostly in consumer electronics, ambient light sensor material and geometries that operate under a wide range of intensities with minimal fabrication and operational cost are of great interest.

Cuprous Oxide (Cu_2O) is a highly researched material in the field of semiconducting devices. It is a naturally abundant, non-toxic, low cost material having a high absorption coefficient and favorable spectral response in the visible range [6]. In this study we investigate firstly, the possibility of utilizing Cuprous Oxide thin film semiconducting material in a $p - n$ junction semiconductor geometry operated in the photovoltaic mode to detect a broad range of ambient light intensity levels. More

specifically, the $p-n$ junction is formed as a Cu_2O/Cu_xS heterojunction semiconducting thin film structure deposited on titanium substrates using electrochemical deposition which is a low cost material deposition technique [7]. Secondly, by interfacing the fabricated photo-sensor we construct a low cost standalone ambient light intensity level measurement device with associated electronics.

Cu_2O is a native p -type, metal oxide semiconductor. It has a direct optical band gap between 2.1-2.6 eV that depends on the fabrication method and stoichiometry [8]. The unique physical and chemical properties exhibited by Cu_2O are utilized in photovoltaics, field-effect transistors, various types of sensors and photo-electrodes in high-efficiency photo-electrochemical cells. Recently, it has been demonstrated that sulfidation of electrodeposited n -type Cu_2O films can drastically improve conductivity leading to higher short circuit currents and open circuit voltages compared to unsulphided n -type Cu_2O thin films [9]. It is also considered one of the most feasible routes to form a semiconducting heterojunction with n -type Cu_2O . Electrochemical deposition technique was employed as the preferred method for growing the Cu_2O thin films due to the ability to fabricate n -type large area films at temperatures close to room temperature with relative ease of operation and lower cost.

The electronics of the standalone ambient light intensity measurement device consists of three major signal acquisition and processing segments that includes photo-sensor interface, amplifier for the detected photo-voltage amplification, analog to digital conversion of the amplified signal, scheme to convert the measured photovoltage to light intensity in the units of lux, serial communication link for data logging and a data display based on a liquid crystal based (LCD). The device was operated either in a real-time measurement mode or in a mode able to make measurements on a pre-programmed request basis. Also the fabricated photo-sensor operated in the photovoltaic mode therefore, required no external voltage supply for biasing. However, a large load resistance was needed to keep the current flow low through the sensor.

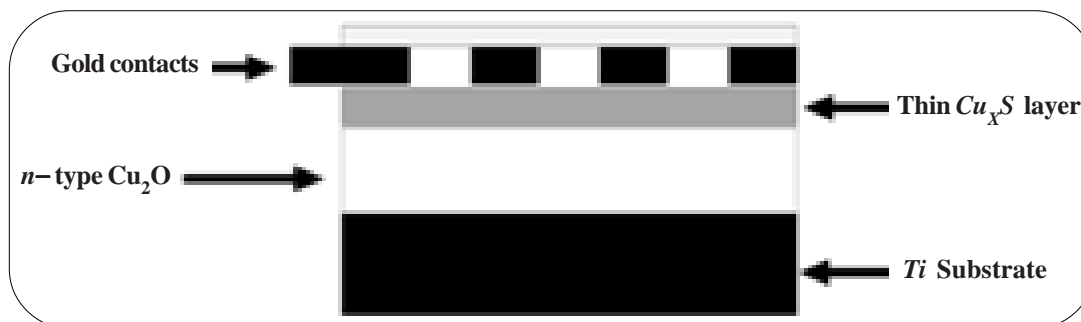


Figure 1. Design of the Cu_2O/Cu_xS heterojunction photo-sensor

2. Design of the Device

2.1 Fabrication of the Sulphided Cu_2O Thin Film Photo - Sensor

Cu_2O thin films were deposited on titanium (Ti) substrates. Before the deposition, substrates were cleaned with detergent by brush abrasion technique, and then with diluted Hydrochloric (HCl) acid and finally with distilled water. Cleaning methods were designed to minimize substrate damage while removing any organic impurities or debris on the substrate. For electrochemical deposition, 0.01 M Cupric Acetate and 0.1 M Sodium Acetate were added into the electrochemical cell. A saturated calomel electrode, a platinum plate and a titanium plate were used respectively as the reference, counter and working electrodes of the electrochemical cell. The temperature of the electrolyte was maintained at 60°C and the electrolyte was continuously stirred using a magnetic stirrer. The deposition was carried out under a potentiostatic condition of -200 mV vs. saturated calomel electrode for 60 minutes. pH value of the electrolyte was adjusted by adding a dilute sodium hydroxide solution to the bath. The general trend is that for high cupric ion concentrations, the films deposited at low pH values are n -type and those deposited at high pH values are p -type [10]. Formation of a Cu_xS/Cu_2O junction was achieved by directly applying a Na_2S aqueous solution on to an n -type Cu_2O thin film followed by heating on a hot plate at 100°C. When reacted with aqueous Na_2S , Cu_2O is converted into Cu_xS the process is termed sulphidation. After the sulphidation, the sample was washed thoroughly with distilled water to remove any excess Na_2S and NaOH that was formed during sulphidation process. Subsequently, the sample was annealed in a

pre-heated oven at 150°C for 10 minutes to increase the photo voltage. Contacts to the film were made using evaporated gold. The resulting samples produced high photovoltages and low photocurrents. Then the sample was directly exposed to ammonium sulphide gas for shorter durations (lower than 2s) in order to further reduce its resistance that resulted in a larger photo current. Finally it was washed using distilled water and annealed at 150°C for 10 minutes. A cross section of the sensor is depicted in Figure 1.

2.2 Signal Detection Electronics

The signal detection electronics are depicted in Figure 2. Fabricated photo-sensor was coupled to the device by carefully placing it on a mechanically adjustable holder. Printed circuit board (PCB) design software (Ivex Winboard, Ivex Design International) was used to lay down all the necessary circuits on copper plates.

2.2.1 Photo-sensor Signal Amplification

Initially, the photo voltage generated by the photo-sensor was amplified by a precision instrumentation amplifier (INA122, Texas Instruments) for accurate, low noise differential signal acquisition. Its two op-amp design provides excellent performance with very low quiescent current, and is ideal for portable instrumentation and data acquisition systems. The gain of the amplifier (G) is given by (1).

$$G = 5 + \frac{200k\Omega}{R_G} \quad (1)$$

Here R_G is an external resistor connected between pins 1 and 8 of the amplifier. The external resistor can be suitably chosen to detect a given range of photovoltages from the sensor. The output of the amplified signal was next input to an in-built 10-bit analog to digital voltage converter module of a microcontroller (PIC16F877A, Microchip) where the reference voltage was maintained at 5 V. (Notice, by picking $R_G = 1 k\Omega$ makes the gain of the amplifier $G = 205$. Therefore, for the 10-bit A/D voltage converter with reference voltage of 5 V allows the detection of photovoltages up to 24.39 mV at 0.024 mV resolution). A 4 MHz crystal oscillator was used to provide the clock signal for the microcontroller.

2.3 Programming the microcontroller

A development tool for PIC microcontrollers, microC PRO (MikroElektronika) an integrated development environment was used to program the microcontroller. Device control, signal acquisition and processing algorithms were implemented using C language. The program control flow chart is shown in Figure 3.

2.3.1 Initialization and Control of the LCD

In order to display measurements, an LCD was integrated to the microcontroller. LCD inputs (3-8) were connected to port B of the microcontroller (RB0-RB5) while, inputs 1 and 2 were connected to the supply voltages. The LCD initialization was achieved using, `Lcd_Init()` a default routine available in microC PRO.

2.3.2 Initialization and Control of the UART Module

Data were also serially transmitted using the serial RS232 port to a PC. The serial transmitter/receiver pins (RC7/RX) of the microcontroller was sent through a universal asynchronous receiver/transmitter (UART) module (MAX 232, Texas Instruments) to convert to RS 232 standards. The UART module initialization was achieved using routine, `UART1_Init()` in microC PRO with baud rate set at 9600.

3. Results of the Experiment

3.1 Response of the sensor under ambient light

Initial measurements were made to estimate the photo responsive range of the photo-sensor. The sensor terminals were connected to a multimeter and the photovoltage was measured under daylight. Simultaneous measurements were also made using a standard luminance meter in order to compare the sensor photovoltage with the corresponding ambient light intensity level in units of lux. The graph in Figure 4 shows the sensor photovoltage response observed under day light intensities compared to simultaneous luminance meter measurements. The trend confirms that the sensor responds to a broad range of ambient light intensity levels while photovoltage being highly correlated with the luminance meter measurements.

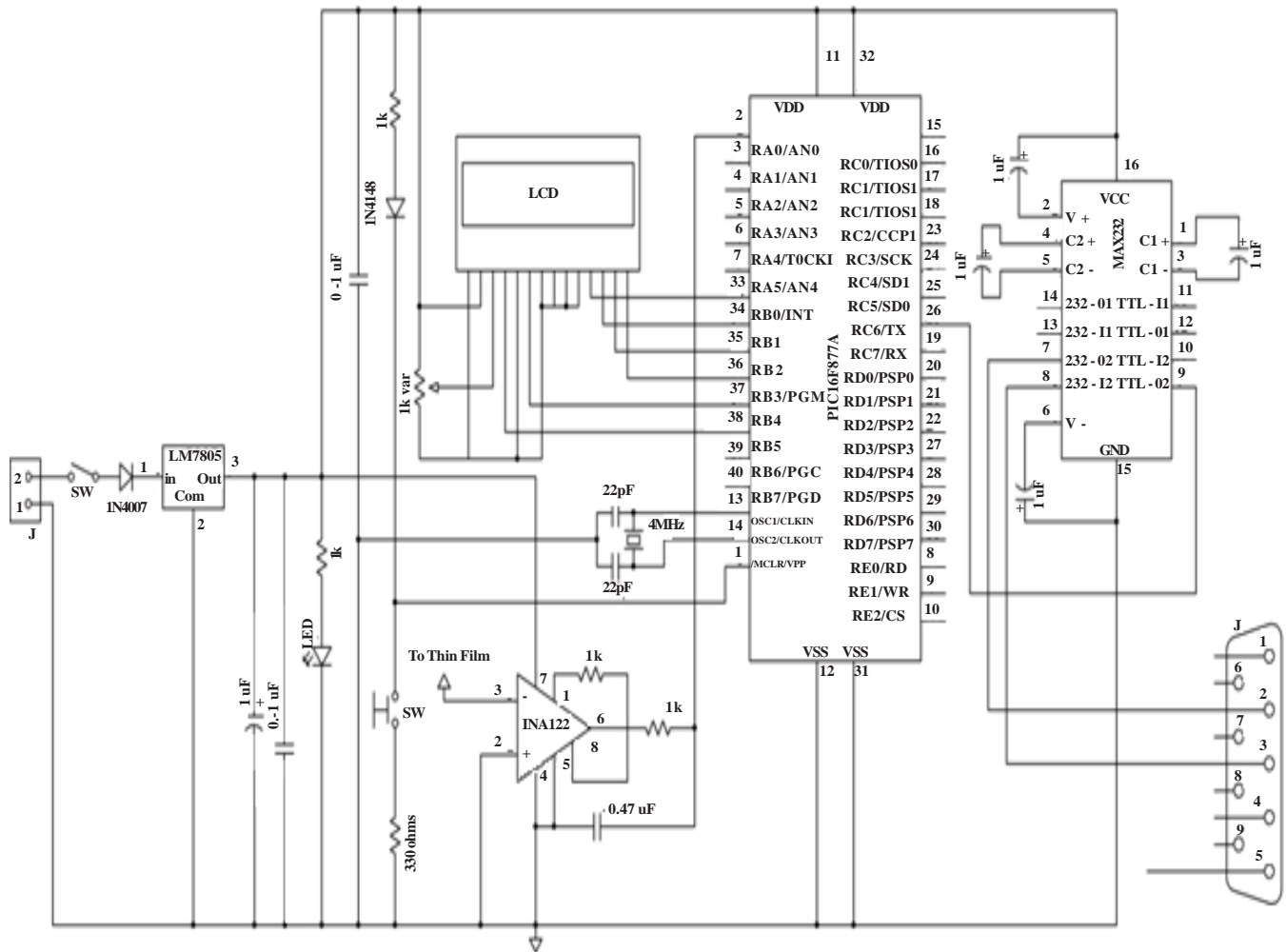


Figure 2. Circuit diagram of the device: The photovoltage generated by the sensor was amplified by a precision instrumentation amplifier shown as AMP in the diagram. The LCD inputs are shown by the rectangle numbered from 1 to 8 adjacent to the microcontroller module. The UART module (MAX 232) is shown on the right of the microcontroller.

3.2 Temporal response of the device

The photo response time of a sensor which is an important parameter was also measured. For this purpose a manually operated 25 W incandescent lamp was used. The lamp at the ON state induced a 500 lux incident intensity level on the photo-sensor as measured by the luminance meter. Next by alternating the lamp ON/OFF state the sensor photovoltage was measured. The temporal response of the sensor photovoltage is shown in Figure 5. The observed sensor photovoltage ON/OFF transition was quick where the sensor photovoltages reached maximum within a few 100ms.

3.3 Stability of the sensor photo-voltage

Furthermore, to characterize the stability of the photo response of the photo-sensor under a given light intensity, the sensor output photovoltage was monitored continuously for a period of 35 hours under a fixed light intensity of 500 lux that was incident on the photo-sensor at a controlled temperature of 28 °C. The measured photovoltage showed voltage variations of less than 1%.

3.4 Temperature dependence of the sensor photo-voltage

To estimate the temperature dependent variation of the sensor output voltage, the photovoltage was measured under fixed light (25W incandescent lamp) intensity of 500 lux in a temperature range of 17 °C to 28 °C. It can be observed from Figure 6 that the sensor output voltage decreases with increasing temperature due to reduced photo-activity. Hence fluctuations in temperature would need to be carefully considered when light intensity measurements are made.

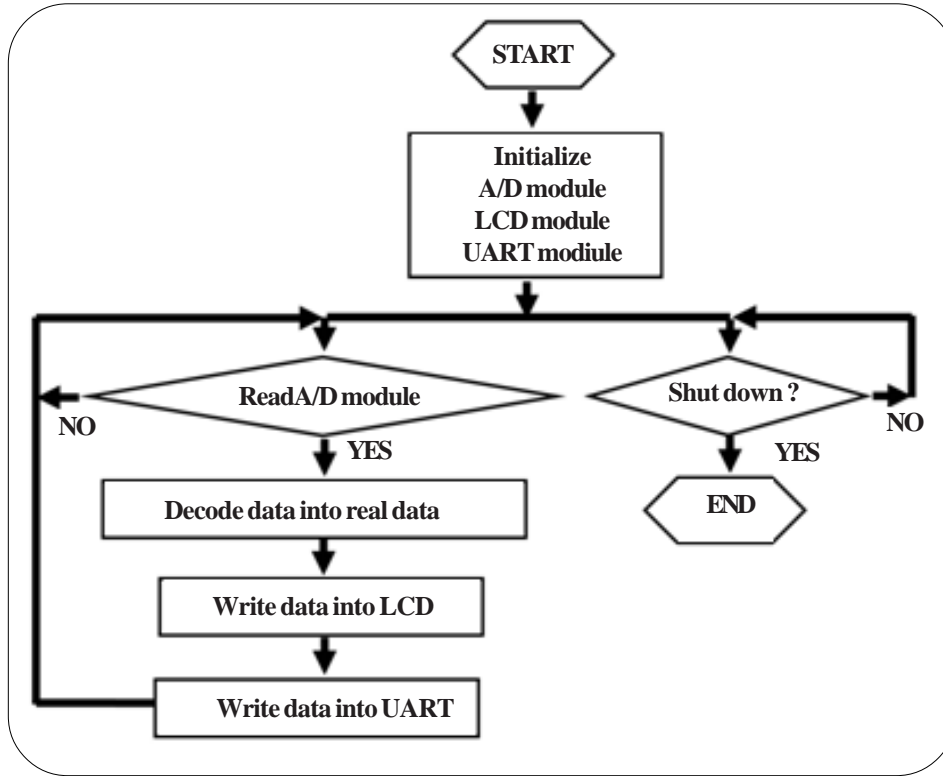


Figure 3. Control flow chart of the microcontroller

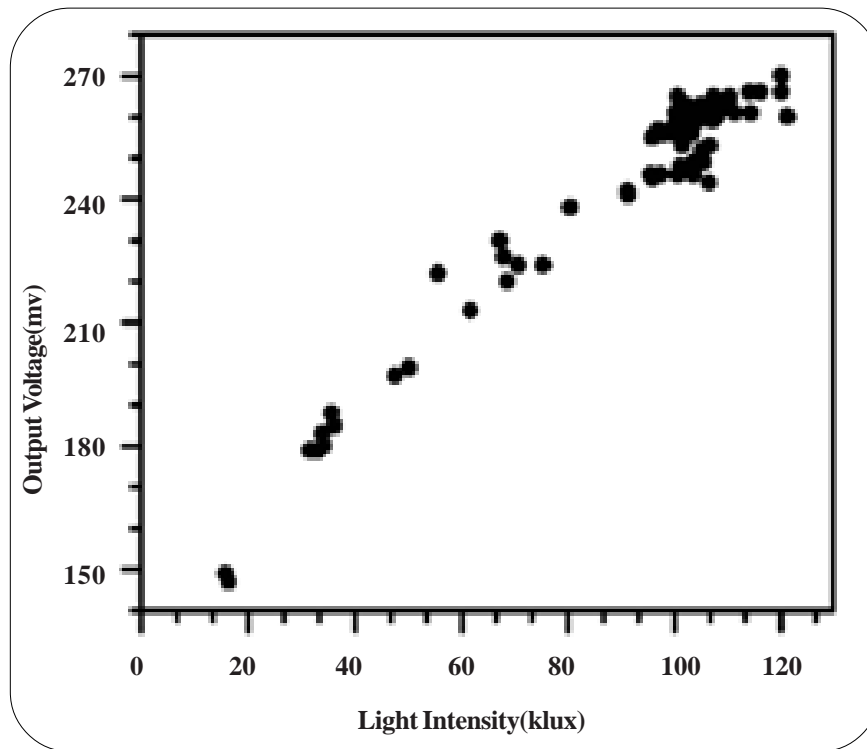


Figure 4. Sensor output voltage vs. the corresponding luminance meter measurements made during day time under variable light

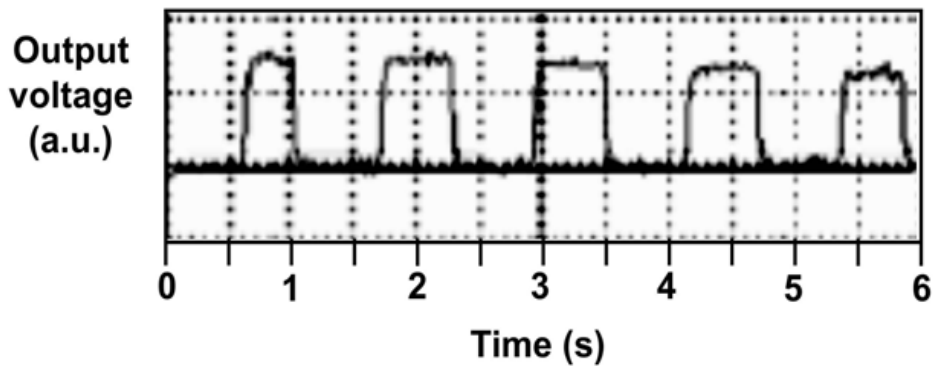


Figure 5. The sensor output voltage response measured during an ON/OFF sequence of a light source

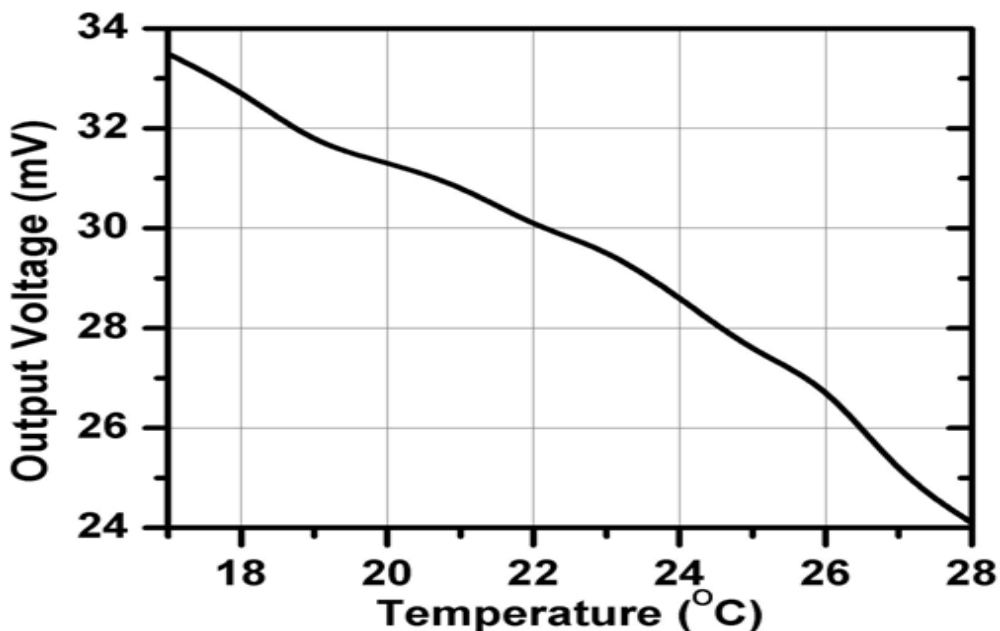


Figure 6. Variation of sensor output voltage with respect to temperature at fixed light intensity (500 lux)

3.5 Calibration measurements for the sensor

In order to calibrate the device, the sensor was exposed to a stable light source (fixed 25W incandescent lamp with the ability to vary light intensity externally) at 28 °C. For a range of different light intensities, simultaneous measurements were recorded from both the luminance meter and the device sensor. To demonstrate the function of the device, the chosen amplifier external resistance (R_C) allowed the measurement of intensities in the range of 0-680 lux at a precision of 1 lux. The photovoltage and intensity measurements from the calibration are shown in Figure 7. The variation was characterized using (2) given by,

$$I(x) = -0.0001x^3 + 0.5139x^2 + 15.0809x + 4.6650 \quad (2)$$

Here x represents the sensor output voltage and $I(x)$ represent the ambient light intensity in units of lux. This calibration function was programmed into the microcontroller to convert a sensor photovoltage to the corresponding intensity level.

3.6 Ambient Light Intensity Measurements from the Device

In order to validate the device, variations of day light intensities (morning and evening) were measured from the calibrated device. The measurements were then compared with the luminance meter measurements as shown in Figure 8. The measurements made by the device were in general within 5-10% of the luminance meter measurements.

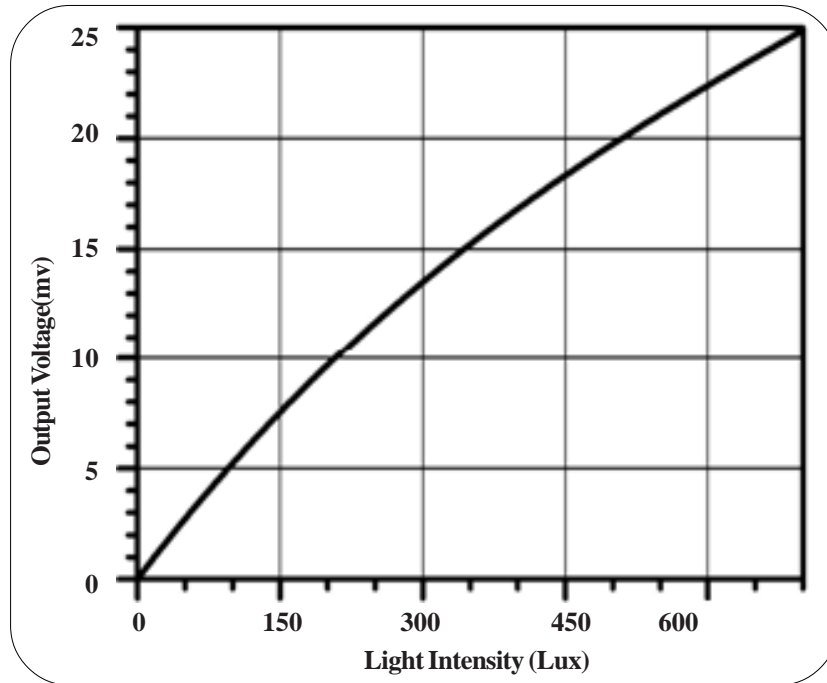


Figure 7. Calibration data for the photo-sensor. The graph shows the output voltage of the sensor versus the light intensity measured by the luminance meter in units of lux

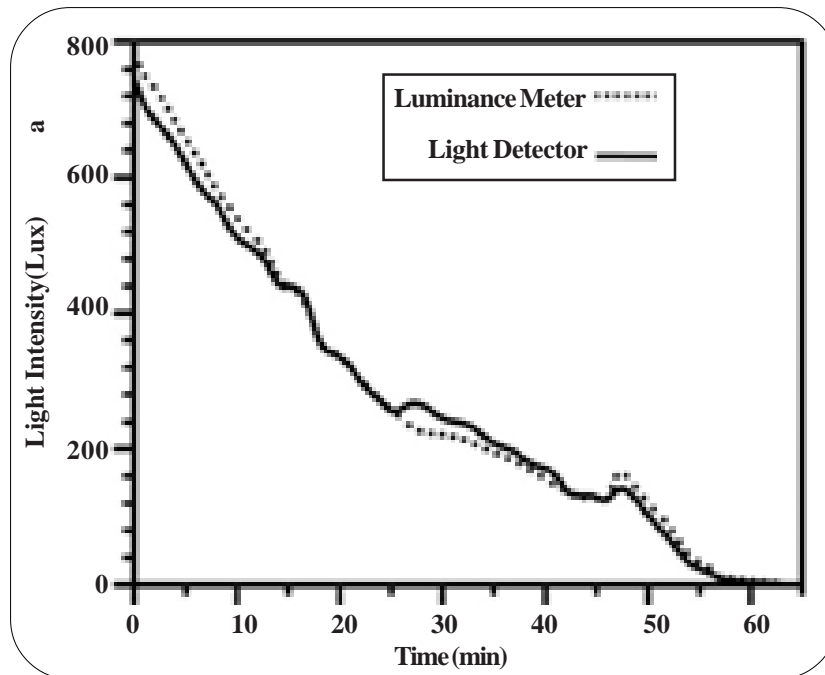


Figure 8. Light intensity measurements made out doors under daylight. (a) During sunset

5. Conclusion

Ambient light sensing finds many applications in consumer electronics. A photo-sensor was developed based on a thin film Cu_xS/Cu_2O heterojunction obtained by sulphidation of n -type Cu_2O which was deposited on a Ti substrate using electrochemical

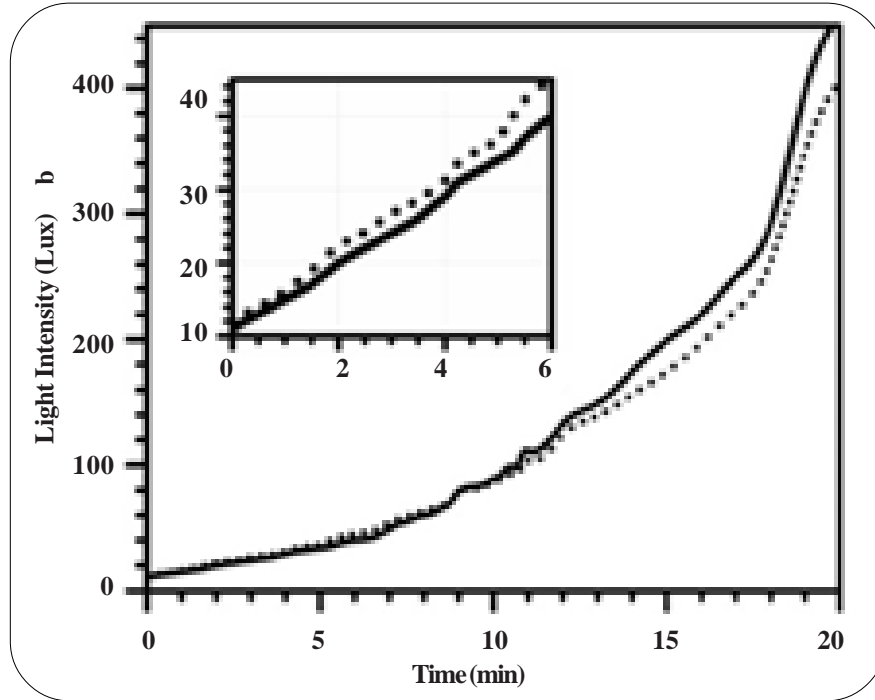


Figure 8. (b) During sunrise, the inset shows the zoom-in of low intensity measurements

deposition. The sensor showed sensitivity to a broad range of ambient light intensities (0 – 120,000 lux). The fabricated photo-sensor showed a stable photo response under constant intensity levels whereas the photo response time of the photo-sensor was on the order of a few 100 ms. The performance of the photo-sensor under variable sensor temperatures showed an approximately 3% per degree °C variation in the sensor output photovoltage. A portable ambient light measurement device was constructed by interfacing the photo-sensor to a microcontroller and operating the sensor in the photovoltaic mode. The measurements made by the device were compared with the measurements made by a standard commercially available luminance meter and were within 5-10% of each other. For the tested range of intensities, the utilized 10-bit A/D converter yielded a measurement precision of 1 lux. However, with the aid of a higher resolution A/D converter the measurement precision could easily be made more precise. Furthermore, variable amplifier gain control could be introduced to measure the full range of intensities sensitive to the photo-sensor. Measurement accuracy could be further improved by introducing temperature dependent feedback temperature dependent sensor effects could be further compensated if is introduced. The total cost of parts for the device was less than US\$25.

References

- [1] Cook Diane, J. (2012). How Smart Is Your Home?, *Science*, 335, p. 1579.
- [2] Cook, D. J., Juan, C. A., Vikramaditya, J. R. (2009). Ambient intelligence: Technologies, applications, and opportunities, *Pervasive and Mobile Computing*, 5.4, p. 277-298.
- [3] Lim, H. S., Kwon, O. K. (2008). Ambient Light Sensing Circuit with Low-Temperature Polycrystalline Silicon p–Intrinsic–n Diode and Source Follower for Auto Brightness Control., *Japanese Journal of Applied Physics*, 47 (3S) 1919.
- [4] Bai, Y. W., Ku, Y. T. (2008). Automatic room light intensity detection and control using a microprocessor and light sensors., *IEEE Transactions on Consumer Electronics*, 54 (3) 1173-1176.
- [5] Makonin, F., Popowich, S. (2011). *An intelligent agent for determining home occupancy using power monitors and light sensors. In Toward Useful Services for Elderly and People with Disabilities (p. 236-240).*: Springer Berlin Heidelberg
- [6] Abdu, Y., Musa, A. O. (2009). Copper (I) Oxide (Cu_2O) based Solar Cells - A Review, *Bayero Journal of Pure and Applied Sciences*, 2 (2) 8-12, December.

- [7] Jayathilake, K. M. D. C. (2010). Electrodeposited Cuprous Oxide/Cuprous Sulphide Thin Film Solar Cell, University of Kelaniya, Kelaniya. M. Phil, Thesis.
- [8] Olsen, L. C., Miller, W., Addis, F. W. (1982). Experimental and theoretical studies of Cu_2O solar cells, *Solar Cells*, 7 (3) 247–279, December.
- [9] Jayathilaka, K. M. D. C., Kapaklis, V., Siripala, W., Jayanetti, J. K. D. S. (2012). Sulfidation of electrodeposited microcrystalline/nanocrystalline cuprous oxide thin films for solar energy applications, *Semiconductor Science and Technology*, 27, November.
- [10] Jayathilaka, K. M. D. C., Siripala, W., Jayanetti, J. K. D. S. (2007). Donor and Acceptor Density Variation in Electrodeposited Cuprous Oxide thin films, In: *Proc. 23rd Tech. Sessions. Inst. Phys., Sri Lanka*.