"Range of illumination for hallways and cafeteria"

Term Project

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Human Factor in QAS, QAS 515

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Introduction and Problem Statement

The purpose of this paper is to use Human Factors Engineering theory to adapt the range of illumination in hallways and cafeteria required for night shift operators working in a yellow light cleanroom of a semiconductor Fab, to reduce glare discomfort and increase performance.

Background

A company that uses semiconductor technology to manufacture electrochemical sensors at the micrometer size on silicon wafers, use photolithography processes which are based on the use of light sensitive material, also known as photoresist, deposited on the surface of the wafer to be exposed to ultraviolet (UV) light through a mask that will allow certain areas of the photoresist layer to be exposed to such light to draw the desired pattern that will be etched away in the next process, thus building the sensor that will eventually be sliced from the wafer to have individual dies. Depending on the sensor is the amount of layers that will be patterned using photolithography technology and the photoresist mentioned above.

The photoresist is a mixture of photosensitive compounds, base resins, and organic solvents. Prior to exposure to light, this mixture is insoluble in the developer solution. The purpose of this developer solution is to dissolve the unwanted photoresist and keep only the patterned material needed during the dry etching process, where the pattern is transferred from the photoresist to the surface of the wafer. After the desired area of the photoresist is exposed to UV light, the absorbed radiation is converted in chemical energy initiating a polymer cross-linking reaction. The cross-linked polymer will have a higher molecular weight becoming insoluble to the developer solution, thus keeping the desired pattern on the wafer and dissolving the undesired material away.

The laboratories where these processes are carried out in the semiconductor industry are known as “fab”. The fab is a temperature, humidity, particle count, and light controlled environment workstation. Some fabs have yellow light only were the photoresist is being deposited, developed, and etched away, other fabs have yellow light in he entire facility. One property of the photoresist is the sensitivity, or amount of light of the desired wavelength, at which the crosslinking reaction will initiate. The crosslinking reaction in the photoresist will initiate at a wavelength range of 0.3 to 0.4 µm. This is the range used in the exposure tools to pattern the surface of the wafers, which is accomplished using UV light. The reason for using yellow light in the fab is to control the wavelength of the light sources and eliminate the undesired wavelengths smaller than 0.5 µm. The wavelength of the white light is greater than 0.7 µm, however it also includes wavelengths smaller than 0.5 including the UV and blue light, hence its avoidance. The wavelength of the yellow light is 0.5 µm.

Operators in the fab work 12 hours shifts, there are two night shifts formed of three nights from 6:30pm to 6:30am Sunday to Tuesday one, and Wednesday to Friday the second night shift. Operators have two 15 min breaks and one-hour dinner break. This shift exposes the operator to the yellow light for 10½ hrs. During the break periods they have to travel from the fab to the cafeteria through a one-mile hallway illuminated with white light. This hallway has the ceiling and walls painted bright white, and the floor is painted bright light gray. All surfaces from the hallway, ceiling, walls, and floor are bright, glossy, and highly reflective. Lamps are placed centered and aligned along the ceiling. Once operators arrive to the cafeteria, the same colors and textures of all surfaces as well as the lighting style prevails.

While working in this company with the environment mentioned above, several complaints from operators were placed about the discomfort they experienced when exposed to this bright lighting. They complained about eyestrain and headache. As long as the work environment affects negatively the comfort of the worker performance will be compromised, errors will be made, fatigue will start, and sick leaves may increase. These are good enough reasons to take action and initiate improvement initiatives. Here is where Human Factors Engineering is addressed to eliminate the cause of worker discomfort.

Classification of Stressors in the Workplace Environment

A stressor produces stress, many forms of stressors are:

- Physical Stressors: extremes of temperature, ***lighting***, ventilation and humidity, noise and vibration
- Chemicals Stressors: Dangerous chemicals such as gasses, dust, vapors, and so on
- Biological stressors: Bacteria, viruses, and so on

However, most people associate stress with social or psychological stress which may be brought about perhaps by isolation, rejection, pressure and general overloading of the body system (distress). The demands of people at work vary substantially, some may be related to the actual work that they do or the factors surrounding that work, including:

- Psychological demands: machine-paced work, the quality of supervision, hazards, or monotony of the task
- Physical demands: the effort required, as in manual handling activities, the potential for fatigue, and exposure to hazardous substances
- Demands related to the construction of displays and controls on machinery
- Environmental demands: noise, pollution, ***inadequate lighting***, and so on
- Working hours: ***Shift work***, unsocial hours, ***night work***, or the frequency of breaks
- Payment arrangements: piecework system, or compliance with standards [5].

Workplace Illumination and Human Factors Engineering

Human Factors Engineering (HFE) is the science of analyzing work, and then designing jobs, equipment, tools, and methods to most appropriately fit the capabilities of the worker. Its primary focus within the workplace lies on the prevention of injuries and the improvement of work efficiency. Its economic standpoint approaches two reduction of costs associated with work-related injuries and (lost work-days, workman's comp cost, and associated medical costs), and increased profits through improvement in overall worker productivity. HFE intervention in the workplace does not have to be complicated and can potentially pay considerably dividends when skillfully employed [6].

One of the most critical components of workplace design in terms of both productivity and worker comfort is that of adequate lighting. While the human visual system is functional across a range of 10^{16} levels of illumination, this does not imply that all result in equal performance. Illuminance is the amount of light falling on a surface, while luminance is the amount of light reflected from a surface. To high a level of illumination will result in unacceptable levels of glare (excessive brightness that exceeds the adaptation levels of the eyes), and unacceptable levels of shadow. There are two types of glare, which must be taken into consideration within the manufacturing environment.

The first is direct glare, caused by having the sources of illumination within the visual field of the employee a number of methods can be used to control this problem:

- Decreasing the luminance of the light source
- Reducing the area of high luminance causing the glare
- Increasing the angle between the glare source and the line of vision
- Increasing the level of luminance around the glare sources
- Placing something between the glare source and the line of sight

The second type of glare is reflected glare caused by the reflection of sources of illumination from shiny surfaces and can easily and most easily be minimized by utilizing less powerful sources of illumination or by or by reoriented work so that the light is not reflected into the worker's normal line of vision. Discomfort glare is a sensation of annoyance or pain caused by differences of brightness within the visual field, while disability glare is glare that interferes with visual performance [7].

Capture and Detection of Light by the Human Eye

A beam of light coming from the light source that reaches the cornea of the human eye is refracted by this translucent layer and initially focused. This beam of light then reaches the pupil were the dilator and sphincter muscles of the iris located around the pupil control the amount of light entering the eye. This refracted and focused light beam reaches then the lens where the suspensory ligaments and ciliary muscles will provide a thin and flat or thick and rounder lens surface to suitably refract the light beam to focus distant or close objects. Lastly, the beam of light focused by the cornea and lens will reach the retina. The center of the retina contains the fovea in which the light sensors are located. These light sensors are the rods and cones; rods respond to low-intensity light and cones respond to colored bright light. Rods and cones contain pigments that convert light into electrical signals that are passed along the optic nerve to the brain [1]. Figure 1a shows a general structure of the human eye and figure 1b shows the path of light through the eye to the retina.

Structure of the Human Eye

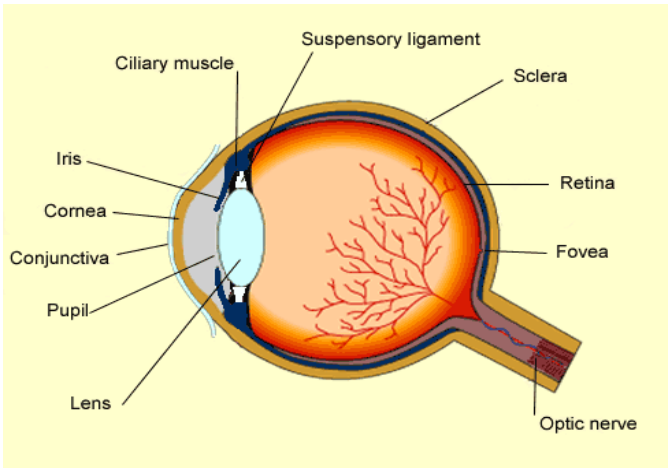


Figure 1a.The human eye, http://www.bbc.co.uk/schools/gcsebitesize/science/images/bieyestructure.gif

Light Path and Detection in the Human Eye

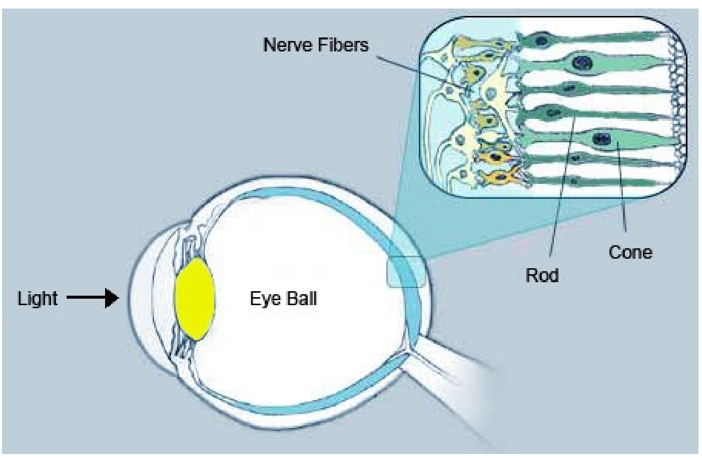


Figure 1b.Light Path in the human eye, http://www.kevinnye.com/images/human-eye.jpg

Optical radiation hazards to the eyes vary greatly with wavelength and also depend upon the ocular exposure duration. Depending upon the spectral region, the cornea, lens and/or retina may be at risk when exposed to intense light. Natural aversion responses to very bright light sources limit ocular exposure, as when one glances to the sun, but artificial sources may be brighter than the solar disk, or have different spectral or geometrical characteristics that overcome natural avoidance mechanisms, and the eye can suffer injury. Photochemical effects scale differently with wavelength, exposure duration and irradiated spot size. Experimental biological studies in humans and animals make use of these different scaling relationships to distinguish which mechanisms are playing a role in observed injury. Photochemical injury is highly wavelength dependant [3].

The human eye is well adapted to protect itself against the potential hazards from optical radiation (UV, visible, and IR radiant energy) from most environmental exposure to sunlight. However if ground reflections are unusually high, as when the snow is on the ground, reflected UV radiation may produce “snow blindness.” Another example is during a solar eclipse, if one stare at solar disk from more than 1 or 2 minutes without eye protection, the result may be an “eclipse burn” of the retina [4].

Glare Producing Lighting

Glare is created by improper lighting in the workplace. The two main sources are light shining directly into the eye (direct glare) or from reflection from surrounding surfaces (reflected glare). Direct, or discomfort, glare primarily comes from bright sources of light in the field of view. Light often leaves an overhead fixture in a wide angle, resulting in light directly entering the worker’s eyes if they are viewing the work in a near-horizontal viewing angle. To test for direct glare, a simple shielding test should be employed. Have the worker viewing in the normal walking position, then, simply ask them to shield their eyes with their open hand, as if simulating the bill of a cap. They will notice an immediate difference in the comfort level of their eyes; possibly even the physical relaxation of the muscles around the eyes. If this test reveals a significant subjective sense of relief from the worker, then the light source should be redirected or shaded. Reflected glare is another significant factor in worker’s discomfort. This comes from various sources in the workplace such as bright colors [2].

The Visible Light Region of the Electromagnetic Spectrum

Electromagnetic radiation can be considered as a wave that varies as wavelength. Wavelength is defined as the distance between successive peaks in the wave and is measure in nanometers (10^{-3} µm). The range of human vision extends from around 0.4 µm to 0.7 µm and this band of electromagnetic radiation is referred to as light [8]. Figure 2 shows the range of wavelength that forms the visual light region of the electromagnetic spectrum.

Visible Light Waves

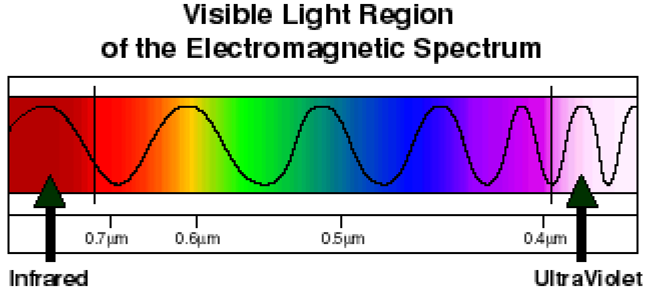
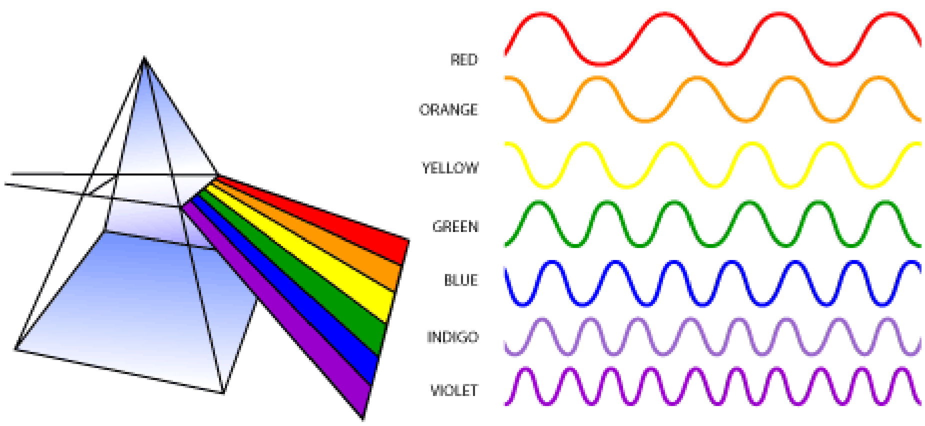


Figure 2. NASA, The electromagnetic Spectrum, http://science.hq.nasa.gov/kids/imagers/ems/visible.html

Visible light waves are the only electromagnetic waves we can see. We see these waves as the colors of a rainbow. Each color has a different wavelength, with red having the longest and violet the shortest wavelength. When all the waves are seeing together, they make white light. Cones in our eyes are receivers for these tiny visible light waves; light bulbs are a source of visible light waves [9]. Figure 3 gives a comparison of the different wavelengths of the visual region of the electromagnetic spectrum.

Wave Patterning of Vary Light Colors



Each color in a rainbow corresponds to a different wavelength of electromagnetic spectrum.

Figure 3. NASA, The electromagnetic Spectrum, http://science.hq.nasa.gov/kids/imagers/ems/visible.html

Night Shift Work

Circadian rhythms are regular changes in mental and physical characteristics that occur in the course of a day. Most circadian rhythms are controlled by the suprachiasmatic nucleus (SCN), also known as the "biological clock", that rests in the hypothalamus, just above the point were the optical nerves cross. Light that reaches the photoreceptors in the retina creates signals that travel across the optical nerve to the CSN. Signals from the SCN travel to the pineal gland, which responds to light-induced signals by switching off production of the hormone melatonin, which controls sleep. The body's level of melatonine normally increases after darkness falls, making people feel drowsy. Most people's biological clocks work on a 24-hour cycle. Sun light or other bright lights can reset the SCN altering worker's circadian rhythms [11].

Shift work sleeping disorders may have short and long-term effects. Employees working in shift work positions for over 10 years have shown drastically increased rates of heart disease and gastrointestinal disease [10].

Measurement of Light Level

Lumen or Watt?

Sometimes the brightness of electric light is associated with the wattage of the lamp bulb. It is the light output measured in lumens and not the watts. A standard incandescent 60-watt bulb provides a specific level of light, but a 18-watt compact fluorescent will generate a greater light output than the former. Both light bulbs give a light output of about 1000 lumens but the standard incandescent bulb produces 15 lumens per watt as opposed to the fluorescent bulb, which generates 50 lumens per watt [18].

Units of Measurement

Luminous intensity (I) is the solid angular flux density in a given direction measured in candlepower in American National Standards Institute (NIST) units and candela (cd) in SI units. The candela and candlepower have the same magnitude. Lumen (lm) is the unit of luminous flux equal to the flux in a unit solid angle of 1 steradian (sr), from a uniform point source of 1 cd.

Illuminance (E) is the density of luminous flux incident on a surface in lumens per unit area. One lumen uniformly incident in one square foot of area produces an illuminance of one footcandle (fc). The unit of measurement, therefore is the footcandle (fc) in ANSI units. In SI units, the measurement is lux (lx), or lumens per square meter.

Luminance (L) is the luminous flux per unit of projected area and a unit solid angle leaving a surface, either reflected or transmitted. The unit is the footlambert (fL), in which 1fL = 1/π candles per square foot. In SI units it is candela per square meter. Luminance takes into account the reflectance and transmittance properties of materials and the directions in which they are viewed (the apparent area). Thus, 100 fc striking a surface with 50 percent reflectance would result in a luminance of 50 fL [12]. Table 1 shows the most common conversion factor for units of illumination.

Conversion Factors of Units of Illumination

Given	*Multiply by*	*To obtain*
Illuminance (E) in lux	0.0929	Footcandles
Illuminance (E) in footcandles	10.764	Lux
Luminance (L) in cd/ sq.m	0.2919	Footlamberts
Luminance (L) in footlamberts	3.4263	cd/sq.m
Intensity (I) in candles	1.0	Candlepower

Table 1. Conversion Factor of Units of Illumination. Electrical Engineer's Portable Handbook, Robert B. Hickey, Mc Graw-Hill professional, 2003, pg 405

A rule of thumb is that 10 fc is equal to I lx.

The illumination levels suggested by the IESNA lighting handbook for cafeteria area and hallways fall under category letters of F (100 to 200 fc) and C (10-20 fc) respectively [14].

Illumination Level Calculation

The number of luminaries required to light a space to a desired illumination level (footcandles) can be calculated with the following the zonal cavity method of calculating illumination stated by the equation bellow:

Footcandles = (N x lumens per lamp x CU x LLF) / area per luminaire

Where: N = number of lamps
CU = coefficient of utilization
LLF = light loss factor

The coefficient of utilization (CU) is factor that reflects the fact that not all of the lumens produced by a luminaire reach the work surface. It depends on the light fixture, room size, and the surface reflectances of the room. It's usually included in product catalogues. Light loss factor (LLF) is a fraction that represents the amount of light that will be lost due to dirt, among others. It is calculated multiplying ambient temperature, voltage, luminaire surface depreciation, and non standard components. In absence of that information, a LL factor of 0.9 is used [15].

Reflectance Properties of Paint

Light reflectance value (LRV) is the total quantity of usable and visible light reflected by a surface in all directions and at all wavelengths when illuminated by a light source. It's a measurement that tells how much light a color reflects, it runs on a scale from 0 to 100%, zero assumed to be an absolute black and 100% a perfectly reflective white. The light reflectance value is different from intensity value. Intensity deals with the brightness or dullness of a color, how clear or muted a color is. Figure 4 shows a full scale of LRV [16].

Light Reflectance Value Scale in Paint Color

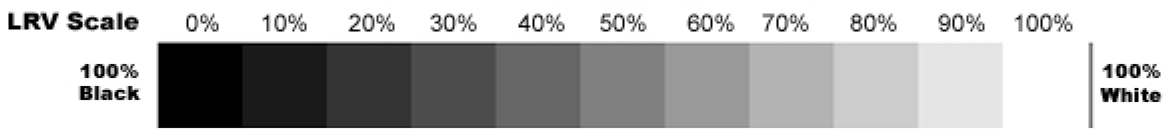


Figure 4. Light Reflectance Value of Paint Color, Squidoo DIY & Hobbies, http://www.squidoo.com/LRV

Gloss Level of a glossy surface is measured according to ISO 2813, 60°. Gloss level instruments illuminate the surface at a 60° angle and measure the reflected fraction of the light. The minimum gloss level is 0 and corresponds to a completely matt surface and the maximum is 100 gloss units corresponding to a very glossy surface [17]. Glossy surfaces high levels of light reflectance.

HFE Countermeasure

There are three actions that can be taken to remove the cause of discomfort in hallways and cafeteria for night shift operators due to high reflectance and high illumination levels.

1. Adjust the illumination range
2. Relocate the light sources
3. Change surface color and texture to control luminance and glare

Adjusting the Illumination Range of Hallway and Cafeteria

Footcandles for the Hallway:

Footcandles = (N x lumens per lamp x CU x LLF) / area per luminaire

Footcandles = (20 x 2500 x 0.62 x 0.9) / 200 = 139.5

Reflectance calculated from white walls:

139.5 fc x 1.0 = 139.1 fc

Reflectance calculated from gray floor:

139.5 fc x 0.8 = 111.6 fc

Footcandles for the cafeteria:

Footcandles = (N x lumens per lamp x CU x LLF) / area per luminaire

Footcandles = (30 x 2500 x 0.62 x 0.9) / 200 = 209.25

Reflectance calculated from white walls:

209.25 fc x 0.1 = 20.93 fc

Reflectance calculated from gray floor:

209.25 fc x 0.8 = 167.4 fc

This HFE countermeasure will consider the illuminance level for the hallway and cafeteria, also considering the reflectance of light from walls and ceilings. These surfaces contribute to glare and eye discomfort due to the reflectance properties of paint color as well as the glossy surfaces produced by the bright colors and paint texture.

Relocating Light Sources

Moving the light sources from the ceiling to the walls and directed toward the ceiling, will reduce direct lighting on the highly reflective surfaces of walls and floors. Providing both indirect lighting and reduction of glare. This sources of reflected light also contributes to the generation of glare, other problem that directly causes eye discomfort and should be reduced or eliminated.

The same human factor countermeasure is suggested for cafeteria.

Changing surface color and texture to control luminance and glare

The change of color for walls from glossy bright white to matte light gray with a light reflectance value of 80% will reduce the level of light reflectance and generation of glare, along with the adjustment of the illumination range. Darkening the color of the floor from glossy bright gray to matte dark gray with a light reflectance value of 40%.

The same human factor countermeasure is suggested for cafeteria.

Conclusions

It is known that night shift workers from permanent or fixed night shifts of three work nights a week and four nights off will take some weeks to adjust their circadian rhythms to their new schedule. After their circadian rhythm has bee adjusted, night shift workers can resume activities and establish a routine. This shift work will cause operators to adapt their family and social schedules to the new life style. Night shift operators will have less quality sleep given to the inherent noise of day-time. It is also known that the lack of sleep can lead to health problems and the destabilization of the circadian rhythm, finding hard to sleep when needed and waking up when expected, as well as being active at a specific time.

As mention before, operators can adapt eventually to a stable or fixed night shift with minimum health consequences, as long as the rest of the physical, social, physiological, and environmental stressors are kept under control.

There are several factors that can change the circadian rhythm of the human body. Those factors can be the change of working schedule, change of eating habits, change of social and family activities, or simply the illumination range of the bedroom during daytime sleep or the workplace during night shift work.

Several human factures countermeasure can be taken into consideration and implement the most effective and efficient solution. In this case, it is recommended implementing the three HFE countermeasure offered which can be considered as a costly solution, but low performance of operators due to lasck of rest may yield higher quality costs coming from low yields, high scrap rates, and documentation error within the manufacturing line of the wafer fab.

During the 10.5 hr shift inside the wafer fab, working under the illumination of light source of 0.5 μm, the human eye is adjusted to that amount and wavelength of light sending that stable light signal to the optic nerve, and thus to the nervous system, establishing a circadian rhythm.

Every time the operator is exposed to the high level of luminance and glare from hallways and cafeteria, that amount and wavelength of light is transmitted to the optical nerve interrupting the operator rest time, from having to spend time adjusting to the new light intensity instead of relaxing to prepare for the next work cycle.

The three human factors countermeasure suggested in this paper are the adjustment of the illumination range, considering surface color and texture for light reflectance and glare generation purposes, as well as lamp light output. The second human factor suggested is the relocation of the lamp and style to the wall, redirecting the light to the ceiling, keeping the same glossy bright white color that is in place at the moment to ensure 100% reflection of the light producing indirect lighting coming from the ceiling. This second countermeasure would not need extra costs from painting. The third human factor countermeasure suggested in this paper is to change the color and texture of paint from walls and floors in the hallway as well as the cafeteria. This countermeasure will reduce the amount of reflected light and generation of glare that are directed to the operator eye causing distress.

Any of the three countermeasures suggested by itself will improve the workplace and provide a more pleasant and healthy work environment for night shift operators. However the combination of the three would give optimum results.

Suggested Future Work

A financial study for the implementation of the above human factors countermeasure is suggested to find the optimum work safety and comfort versus return of investment.

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