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LIGHT EMITTING DIODES AS A PLANT LIGHTING SOURCE

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INTRODUCTION

Electroluminescence in solid materials is defined as the generation of light by the passage of an electric current through a body of solid material under an applied electric field. A specific type of electroluminescence, first noted by Lossew in 1923, involves the generation of photons when electrons are passed through a *p-n* junction of certain solid materials (junction of a *n*-type semiconductor, an electron donor, and a *p*-type semiconductor, an electron acceptor) (cited in Bergh and Dean, 1976). Development efforts to translate these observations into visible light emitting devices, however, was not undertaken until the 1950s. The term, light emitting diode (LEDs), was first used in a report by Wolfe, et al., in 1955 (cited by Williams and Hall, 1978).

The development of this light emitting semiconductor technology dates back less than 30 years. During this period of time, the LED has evolved from a rare and expensive light generating device to one of the most widely used electronic components. The most popular applications of the LED are as indicators or as optoelectronic switches. However, several recent advances in LED technology have made possible the utilization of LEDs for applications that require a high photon flux, such as for plant lighting in controlled environments. The new generation of LEDs based on a gallium aluminum arsenide (GaAlAS) semiconductor material fabricated as a double heterostructure on a transparent substrate has opened up many new applications for these LEDs (Cook et al., 1987).

CHARACTERISTICS AND PERFORMANCE

The following desirable characteristics of LEDs were listed by Williams and Hall, 1978:

- Long life
- Small size and weight
- Ruggedness
- Good temperature stability
- Low drive voltage
- Fast switching times
- Low noise optical switches
- Compatible with integrated circuits
- Tailored wavelength of light emission
- Cold light (minimum heating)

It is obvious that a number of these characteristics are of considerable importance in selecting a light source for plant lighting in a controlled environment facility. Of particular importance is the characteristic that light is generated by an LED at a rate far greater than the corresponding thermal radiation predicted by the bulk temperature of the device as defined by Plank's radiation law . This is in sharp contrast to other light sources, such as an incandescent or high intensity discharge lamp. This is not to imply that the LED does not heat up because not all electrons are converted into photons and such electrons are retained and result in increasing the temperature of the LED.

Power Conversion (Quantum) Efficiency

Since the quantum efficiency of many LEDs is in the range of 1 to 3 percent, it is not surprising that considerable skepticism prevails that an LED could be used for applications that require a high photon output. This is particularly true of many of the commercially available LEDs in the blue, green, yellow and orange region of the spectrum. However, the recently introduced red light emitting LEDs and the new blue light emitting LED exhibit much higher power conversion efficiencies. For example, external quantum efficiencies of some of the high output GaAlAs LED devices fabricated in the early stages of this technology development effort were reported to be around 18 percent at 300° K and 50 percent at 90° K (Cook et, al., 1987). It may be appropriate to point out that a significant number of photons generated by the LED are in fact reflected back into the device and never emitted outside the LED. Thus, internal quantum efficiencies are much higher and efforts have been made to reduce the difference between the internal and external quantum efficiencies normally found in most LEDs, which is basically an optical and materials problem.

The quantum efficiency of the high output GaAlAs LED is dependent on several important considerations. A frequently overlooked factor is that the quality of the semiconductor alloy has a major impact on the external quantum efficiency of this device. Fabrication of the superthick GaAlAs layer having a transparent substrate with a high degree of consistency and reliability is difficult and expensive. Any compromise in these fabrication procedures results in an LED with low quantum efficiencies and output flux. Therefore, effective use of the GaAlAs LED as a plant lighting source is dependent on devices that are fabricated in such a way as to achieve the highest possible external quantum efficiencies.

The temperature of a *p-n* junction of a diode is a function of input power, ambient temperature, heat sink efficiency, and operation mode (continuous or pulsed). Increases in the temperature of the *p-n* junction result in decreased internal quantum efficiencies (Fukuda, 1991). Therefore, external quantum efficiencies are inversely related to the device operating temperatures as reported by Barta, et al. 1992., and drive current shown in Figure 1a and b.

When being used as a plant lighting source, it is often desirable to operate LEDs at as high a forward current as possible to obtain a high photon flux. Since the LED *p-n* junction temperature increases in proportion to the drive current, removal of heat at the active layer of the LED is critical to maintaining LED performance. Unfortunately, the conductive heat transfer rate of the epoxy used for the encapsulation of typical commercially available LEDs is low. The relative power conversion of a typical GaAlAs LED decreases as the forward drive current is increased (Figure 1a). For example, at the manufacturers suggested maximum rating of 50 mA of forward current, the relative power conversion (quantum efficiency) is approximately 75 percent of that when the device is operated at a forward current of 10 mA. When the device is operated at 100 mA forward current, the relative power conversion decreases to 55 percent of that when the device is operated at a forward current of 10 mA. Thus, increasing the forward drive current of a typical epoxy encapsulated LED increases the photon output but significantly reduces the quantum efficiency.

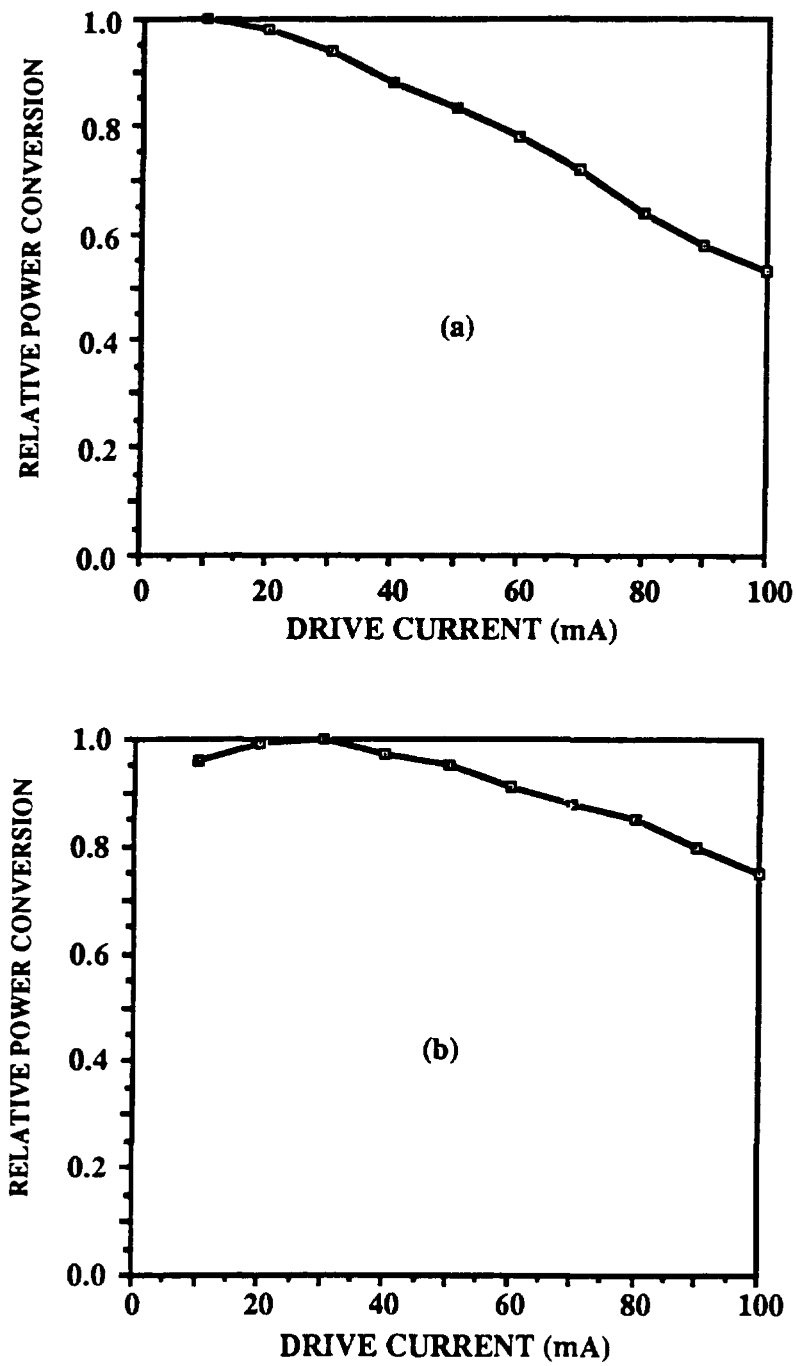

Fig. 1. Relative power conversion of a GaAlAs LED, with a peak emission at 670 nm (a) LED encapsulated in epoxy resin,(b) LED mounted on a proprietary heat dissipation device. (Data from Quantum Devices, Inc.)

On the other hand, when the semiconductor material is mounted in a way that increases the conductive heat-transfer rate over that of an epoxy encapsulated LED, the power conversion when the LED is driven at 50 mA of forward current is approximately 95 percent of that when the LED is driven at its maximum power conversion point of 30 mA forward drive current

(Figure 1b). Even at 100 mA of forward drive current, the LED retains approximately 80 percent of the maximum relative power conversion efficiency. These data clearly demonstrate that if the GaAlAs LED is to be used as a light source requiring a high photon flux, the semiconductor material must be mounted in such a way that the conductive heat-transfer rate maintains the LED at or near the ambient temperature of the environment in which it is operating. Maintaining the LED operating temperature as close as possible to that of normal room temperatures (~300° K) results in the added benefits of prolonging the life and maintaining the photon output during the life of the LED. The LED mounting approach used in the QBeam™ lighting system (Quantum Devices, Inc., Barneveld, WI 53507) utilizes high conductive heat-transfer mounting material which enables the light unit to generate a photon flux exceeding 2000 $\mu mol \cdot m^{-2} \cdot s^{-1}$.

Spectral Composition of the Emitted Light

The peak wavelength of the light emitted by an LED is controlled by the composition of the semiconductor material of the LED, and to a much lesser extent by the operating temperature of the LED. Semiconductor materials are available that have peak emissions ranging from the blue to the infra-red regions of the radiant energy spectrum, the spectral region of most interest for use in plant lighting. For example, the GaAlAs semiconductor can be fabricated so as to have a peak emission over the spectral range of 630 to 930 nm. The most widely available GaAlAs LEDs exhibit a peak wavelength around 660 nm with the spectral energy distribution as shown in Figure 2. An important point is that the peak spectral output of the GaAlAs LED can be fabricated to coincide with the maximum absorption of chlorophyll in the red region of the spectrum. This is an obvious advantage of the LED as a plant lighting source compared to other currently used light sources.

An LED that emits in the blue region of the spectrum is another important component of an LED plant lighting system to the extent that this radiant energy relates to photomorphogenic plant responses. The spectral energy distribution of a recently introduced blue light emitting LED is shown in Figure 3. The semiconductor material of this LED is reported to include alloys of GaN, InGaN, and AlGaN (Anon., 1994). The photon output of this blue light emitting LED is considerably less than that of the red light emitting LED but at least two orders of magnitude higher than any other commercially available blue light emitting LED.

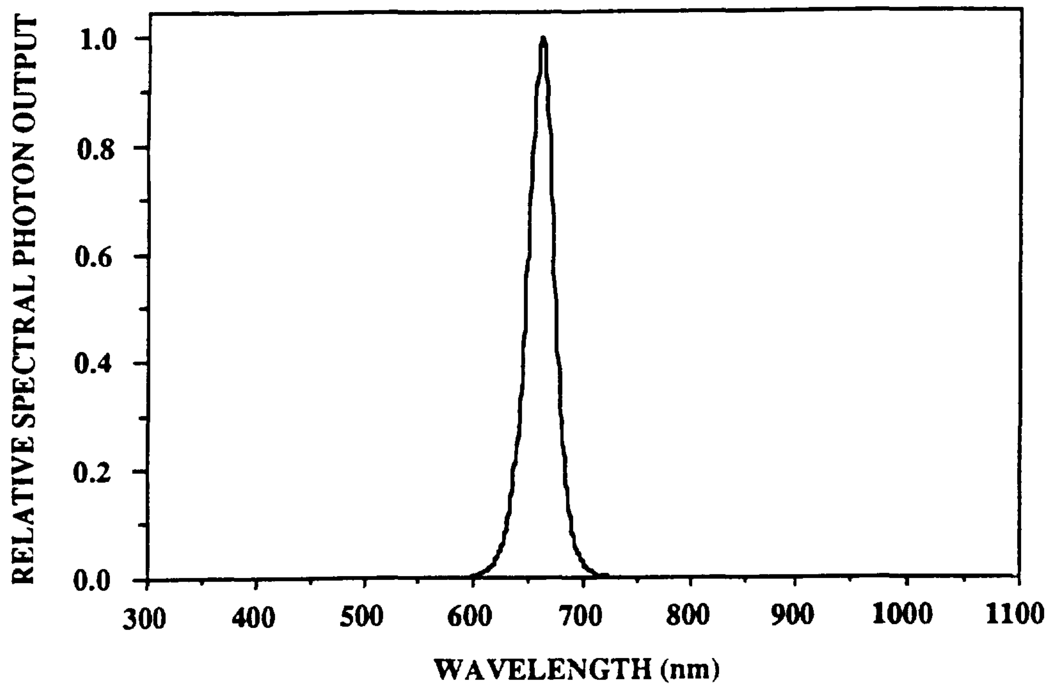

Fig. 2. Spectral photon distribution of a gallium-aluminum-arsenide (GaAlAs) light emitting diode (LED) having a peak emission at ~660nm.

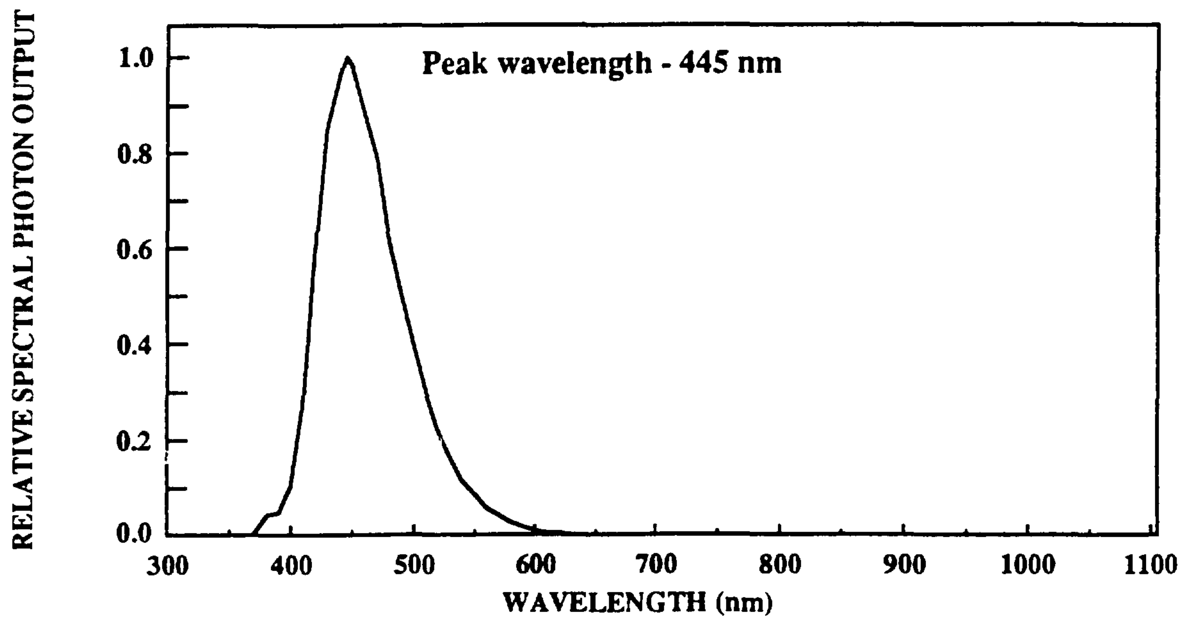

Fig. 3. Spectral photon distribution of a complex gallium-nitride (GaN, InGaN, AlGaN) light emitting diode (LED) having a peak emission at ~445 nm.

The LEDs that emit in the green, yellow, and orange region of the spectrum are based on GaAs, GaP, and/or GaAsP semiconductor materials. The spectral energy distribution of these LEDs varies, depending on the specific composition of the semiconductor. The photon output of these LEDs is rather low and consequently they are of questionable utility in a plant lighting system. Developmental efforts are in progress on these materials and it may be possible that LEDs emitting light in these spectral regions with a higher photon flux will be available in the future.

There is some interest, mostly outside the plant lighting area, in an LED that would emit "white" light. Any such LED would be based on fabrication techniques using multiple semiconductor materials, or chips, rather than one semiconductor material capable of emitting "white" light. Availability of the high output blue light emitting material should facilitate the fabrication of "white" light emitting LEDs at photon flux levels of 50 to 100 $\mu mol \cdot m^{-2} \cdot s^{-1}$.

PLANT RESPONSES

A plant lighting system for controlled environments must provide plants with an adequate flux of photosynthetically active radiation, plus providing photons in the spectral regions that are involved in the photomorphogenic and phototropic responses that result in normal plant growth and development. Use of light sources that emit photons over a broad spectral range generally meet these two lighting requirements. Since the LEDs emit over specific spectral regions, they must be carefully selected so that the levels of photsynthetically active and photomorphogenic and phototropic radiation meet these plant requirements. This does not imply, however, that the LED plant lighting system must provide photons over the entire spectral region of known plant response, namely 380 to 750 nm.

Photosynthesis

Conversion of electrical energy to light energy and the quantum requirement of photosynthesis of a given lamp, are the critical criteria for selection of a light source to provide the photosynthetically active radiation of a plant lighting system. Tennessen et al. (1994a), compared the photosynthetic rates of kudzu (*Pueraria lobata* [Willd] Ohwi.) leaves when the photons were supplied by a xenon lamp or by LEDs with a peak emission in the range of 650 to 664 nm (depending on the intensity of irradiation) over the range of 0 to 1400 $\mu mol \cdot m^{-2} \cdot s^{-1}$. Their results show a typical photosynthetic response curve. At high levels of photon flux, above 300 $\mu mol \cdot m^{-2} \cdot s^{-1}$, and ambient levels of carbon dioxide, the rate of photosynthesis was lower for the kudzu leaves irradiated by the LEDs compared to leaves irradiated by a xenon lamp (Figure 4). However, the photosynthetic response to light intensity was virtually identical for the two light sources when the measurements were made in at elevated levels of carbon dioxide, 175 Pa (Figure 5). These data reflect the potential limitation on photosynthesis by stomatal conductance at low levels of p CO_2 related to stomatal response to red light which will be discussed later. Photosynthetic response of kudzu leaves to increasing concentrations of internal CO_2 partial pressures and at a light intensity of 1000 $\mu mol \cdot m^{-2} \cdot s^{-1}$, was found by Tennessen et, al. (1994a) to be the same whether the photons were provided by a xenon arc lamp or LED lamps (Figure 6).

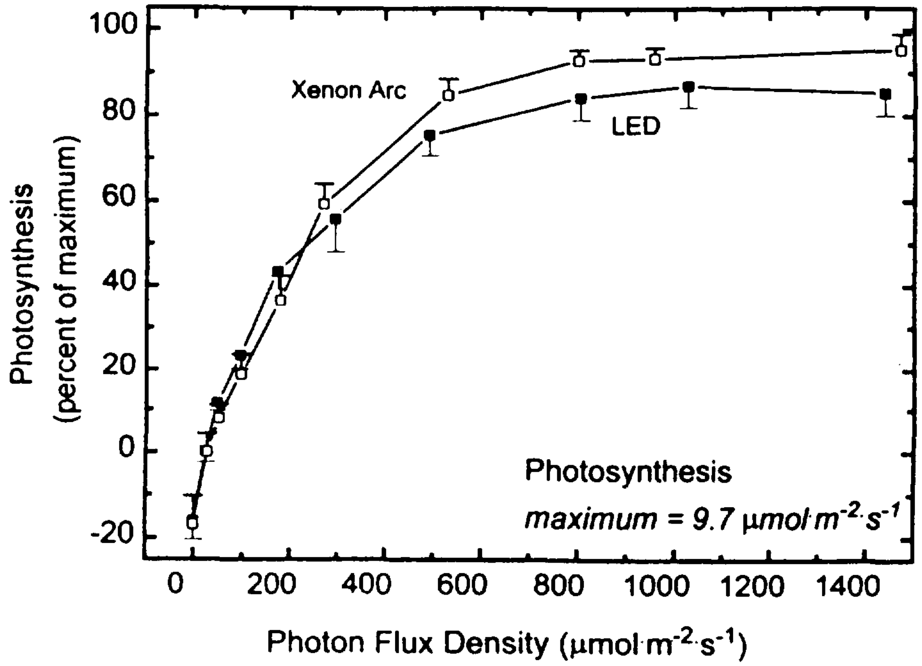

Fig. 4. Net photosynthesis of kudzu leaves, as a percent of maximum in white light, as a response to light intensity from a xenon are lamp (open symbols) and a light emitting diode with a peak emission at ~660 nm (closed symbols), and at a CO_2partial pressure of 35 Pa. (Tennessen et, al., 1994a).

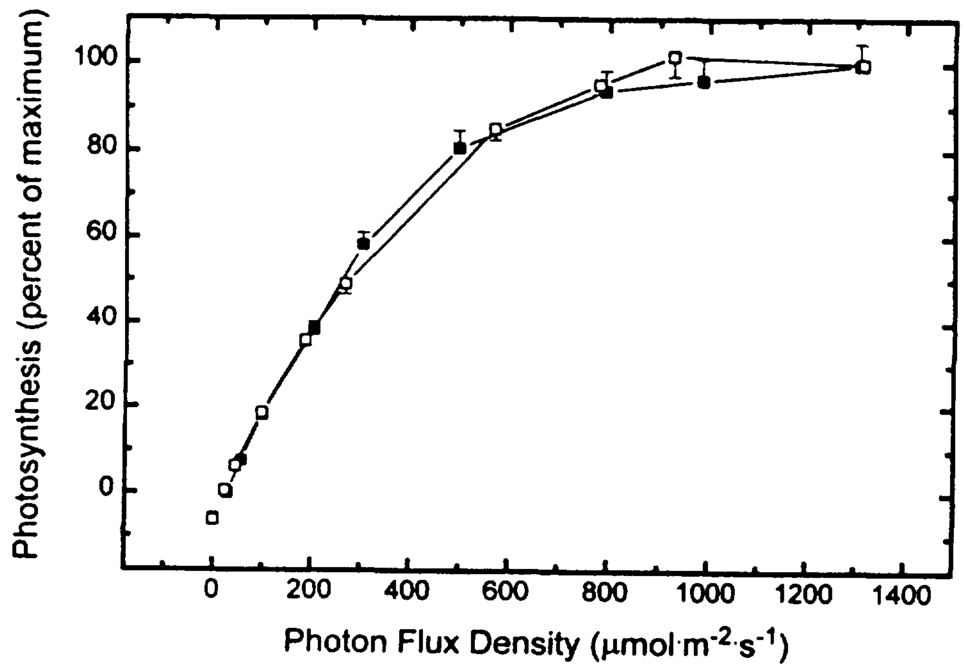

Fig. 5. Net photosynthesis of kudzu leaves, as a percent of maximum in white light, as a response to light intensity from a xenon arc lamp (open symbols) and a light emitting diode with a peak emission at ~660 nm (closed symbols), and at a CO_2 partial pressure of 175 Pa. (Tennessen et, al., 1994a).

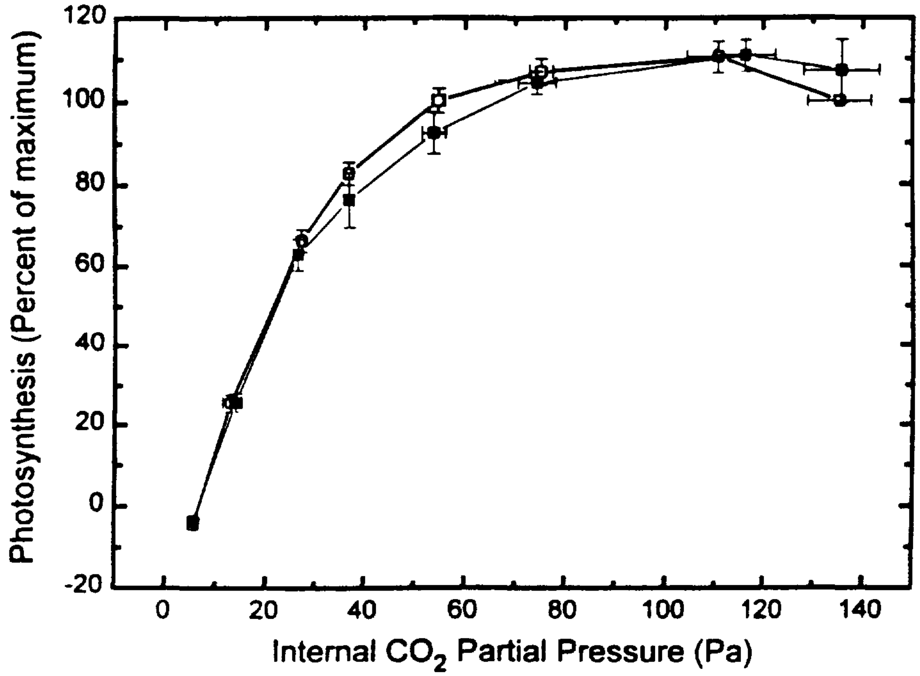

Fig. 6. Net photosynthesis of kudzu leaves, as a percent of maximum, in response to various levels of internal CO_2 pressure and 1000 µmol $m^{-2}s^{-1}$ of light from a xenon arc lamp (open symbols) and a light emitting diode (LED) with a peak emission at ~660 nm (solid symbols). (Tennessen et, al., 1994a).

Tennessen, et al. (1994b), have reported that photosynthesis of tomato (*Lycopersicon esculentum* Mill.) leaves in 2 kPa O_2 (2 %) and 35 Pa CO_2, was nearly linear within the photon flux range of 0 to 50 µmol $m^{-2}s^{-1}$ from LEDs with a maximum emission at 658 nm. The quantum requirement was 10.3 ± 0.6 mol photons mol^{-1} carbon with LEDs having a peak emission at 658 nm, and was not statistically different from the quantum requirement using an LED light sources having peak emissions of 667 and 677 nm. The quantum requirement using an LED light source with a peak emission of 690 nm was 12.3 ± 0.6 and increased to 18.6 ± 0.6 with LEDs having a peak emission at 698 nm. As a comparison, tomato leaves irradiated with cool white fluorescent lamps exhibited a photon requirement of 12.0 ± 0.6 mol photons mol^{-1} carbon in 2 kPa O_2 (Figure 7).

Also shown in Figure 7 are amounts of electrical energy required for the LED lamps having different peak emissions to produce a photon flux of 50 µmol $m^{-2}s^{-1}$. The lowest amount of electrical power (mW) required to fix a µmol of carbon was obtained using LEDs with peak emission in the range of 668 to 675 nm. These observations reflect the increased power conversion efficiency of the GaAlAs LED as the peak emission is increased over the range of 650 to 800 nm. Obviously, photosynthesis is drastically reduced when the percentage of photons beyond 700 nm increases.

These data clearly illustrate that the GaAlAs LED can be an effective source of photosynthetically active radiation. The quantum requirement and electrical energy required to fix a quantity of carbon is less for the LED lamp than for a cool-white fluorescent lamp. In addition, the LED lamps can be a very effective photon source for photosynthetic research to study electron transport, carbon metabolism, and trace gas emission. As technology improvements are made so that the discrete conventional LED is replaced by a monolithic array of diodes, LEDs will become a feasible plant lighting source for controlled environment plant growing facilities.

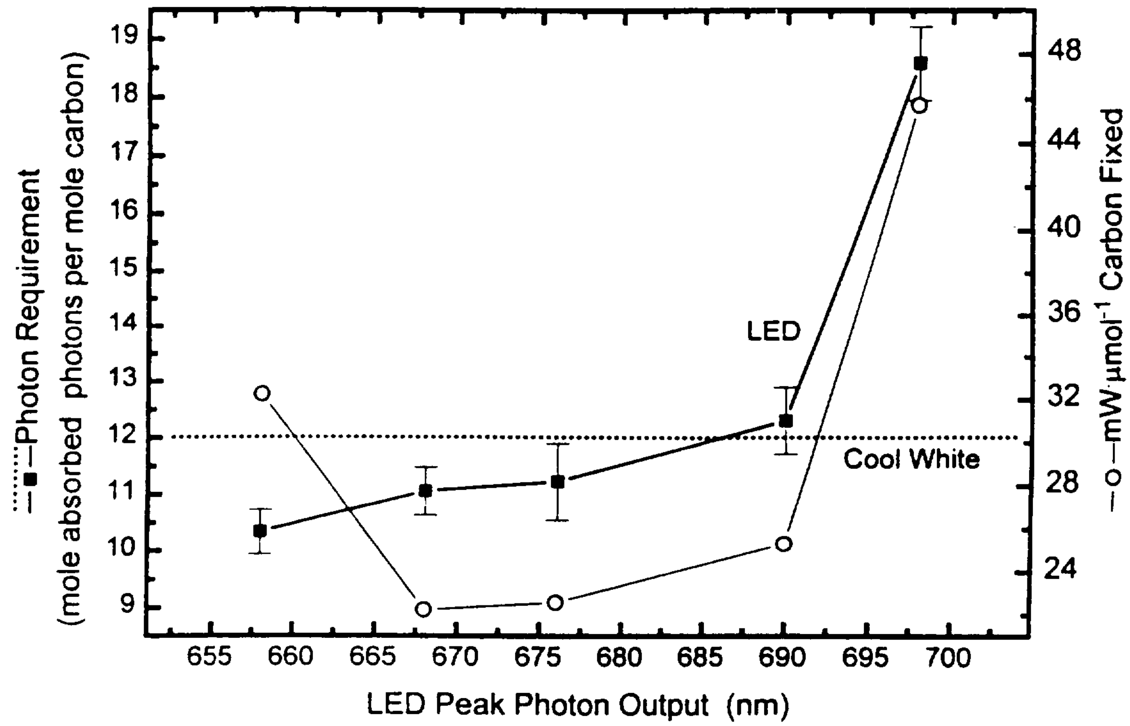

Fig. 7. Quantum requirement of photosynthesis and LED electrical conversion efficiency as affected by spectral quality of light provided by light emitting diodes (LEDs) (solid symbols) or by a cool-white fluorescent lamp at irradiance levels of 50 µmol $m^{-2}s^{-1}$. Electrical conversion efficiency (open symbols) is calculated as mWµmol $carbon^{-1}$, based on the product of mWµmol $photons^{-1}$ and quantum requirement. (Tennessen et, al., 1994b).

Pulsed Lighting

The switching characteristics of LED are desirable for applications requiring pulsed light. The LED can be pulsed at frequencies as high as 100 MHz. We have measured near instantaneous irradiance levels of as much as 5000 µmol·m^{-2}·s^{-1} from LEDs pulsed at KHz frequencies. The LED is an ideal lighting device to study comparative photosynthetic rates under pulsed and continuous irradiation. There are indications in the literature that plants may more efficiently utilize light if it was provided to the leaf as an intense pulse rather than as a continuous flux. However, Tennessen et al.,(1994b), have observed that photosynthetic rates of tomato leaves were equivalent when the light was provided as a pulse of 5000 µmol·m^{-2}·s^{-1} when on 1 % of the time (1.5 µs on and 148.5 µ s off) compared with a continuous photon flux of 50 µmol·m^{-2}·s^{-1} (Figure 8). All the comparative light treatments shown in Figure 8 provided the same level of photons integrated over an equivalent time period. Thus, electron transport of the photosynthetic apparatus appears to act as an integrator of photon flux pulses. The general observation that photosynthetic rates of leaves declines with increasing light levels appears to be a consequence of limitations from downstream reactions and not an inherent limitation of the primary photochemistry of electron transport as may have been previously hypothesized.

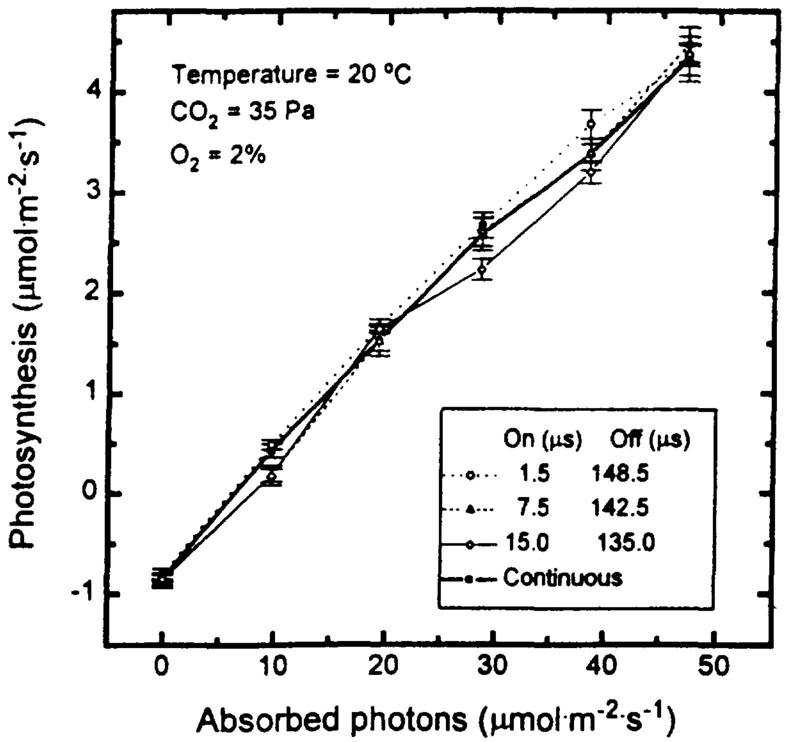

Fig. 8. Photosynthetic response of tomato leaves to increasing amounts of absorbed photons provided in pulsed segments of 1.5, 7.5, and 15 µs during a cycle time of 150 µs. The integrated photon flux of the pulse treatments were equal and the same as a continuous photon flux of 50 µmol $m^{-2}s^{-1}$. (Tennessen et, al., 1994a).

Photomorphogenic Responses

Radiant energy in the blue spectral region has been shown to affect the morphological characteristics of a number of plant organs. Early in the evaluation of the red light LEDs, it was observed that lettuce (*Lactuca sativa* L.) and other dicotyledonous plants developed excessive hypocotyl elongation, stem elongation, leaf extension, and reduced chlorophyll when grown under red light emitting LEDs as the sole source of irradiation. These abnormal morphological characteristics were eliminated and normal plant development occurred when light from the LEDs was supplemented with blue light from fluorescent lamps (Bula, et al., 1991).

Chlorophyll synthesis and chloroplast development appear to be affected when seedlings are grown under red light only. No critical data are available that provide an explanation of these observations or the impact these plant responses may have on seedling growth and development. These general observations indicate that supplementation of red light with a small quantity of blue photons would eliminate such effects and result in normal seedling development.

Hypocotyl elongation of lettuce seedlings appears to be a very sensitive indicator of the amount of blue photons required to support normal photomorphogenic plant development. Using hypocotyl elongation as an indicator of plant response to the presence or absence of blue photons, Hoenecke, et al. (1992), reported normal lettuce seedling hypocotyl development when the red light from LEDs was supplemented with more than 30 µmol $m^{-2}s^{-1}$ of photons in the blue spectral region (Figure 9). The other interesting observation was that the hypocotyl elongation response was regulated by the flux of blue photons and not by the ratio of blue to red photons.

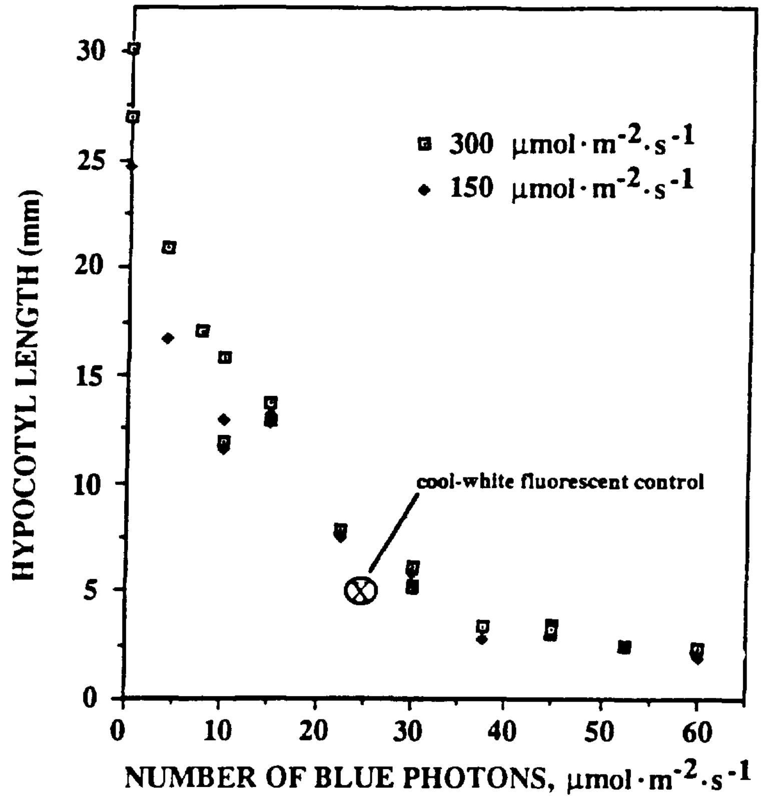

Fig. 9. Relationship between lettuce seedling hypocotyl length and flux of blue photons at two photosynthetic photon flux levels provided by light emitting diodes (LEDs) with a peak emission at ~660 nm and fluorescent lamps having a 246 phosphor that emits photons primarily between 435 and 470 nm. the cool white fluorescent response was at an irradiance level of 150 µmol $m^{-2}s^{-1}$ (Hoenecke, et al., 1992).

Flowering and seed development of several species of plants grown under a combination of red light emitting LEDs supplemented with 30 µmol $m^{-2}s^{-1}$ of blue light were similar to plants grown under light from cool-white fluorescent lamps. Thus, normal plant growth and development can be expected with most , if not all, plant species when grown under red light emitting LEDs as the source of photons for photosynthesis and supplemented with a small quantity of blue photons to meet the photomorphogenic requirements involved in normal growth, development, and maturation.

Stomatal Response

The classical observation that stomates open in light and close in the dark is an over simplification of stomatal response as it relates to stomatal conductance of CO_2 into the leaf. A number of internal and environmental conditions are involved in this critical plant response. From the standpoint of using red light emitting LEDs, Sharkey and Raschke, (1981), reported that stomatal opening was most responsive to light in the blue region of the spectrum, with a peak response being at approximately 450 to 460 nm (Figure 10). However, red photons provide sufficient signal for stomata to open so that the effects of low stomatal conductance under red light can only be overcome by increasing the concentration of CO_2 to higher than ambient levels (Tennessen, et al., 1994). We have recently determined that providing a low level of blue photons from blue light emitting LEDs increases stomatal conductance and has the same effect on photosynthetic rates as was the reported effect of high CO_2 concentrations (unpublished data).

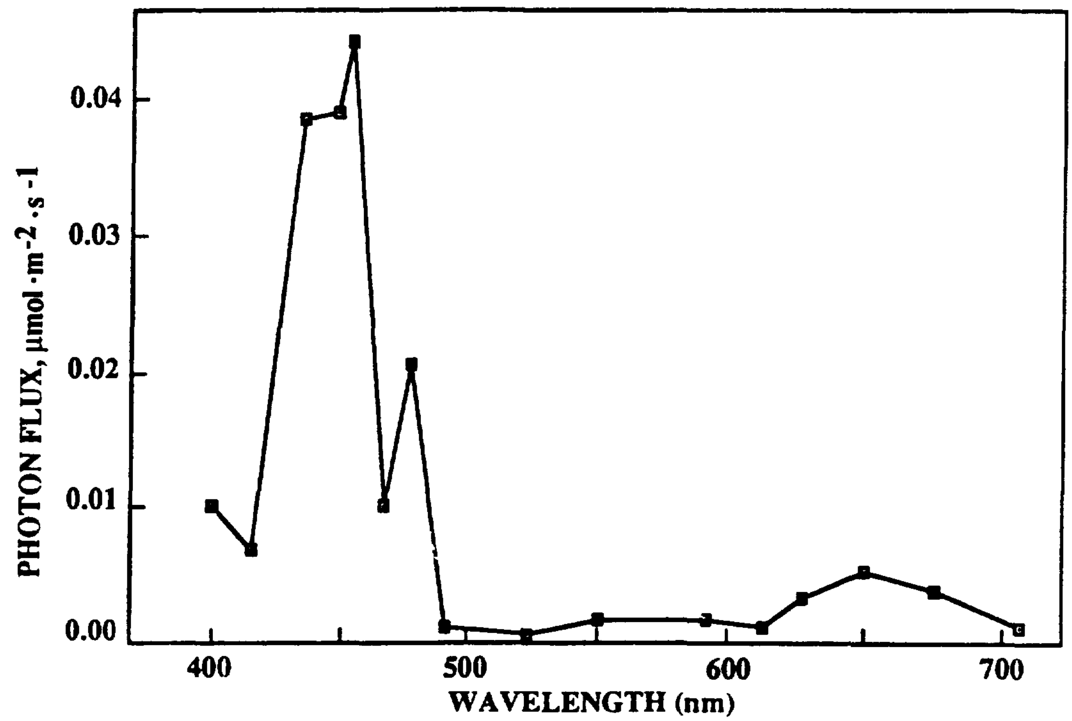

Fig. 10. Action spectrum of stomatal opening in the lower epidermis of leaves of *Xanthium strumarium*, indicated as the inverse of the photon flux required to produce a conductance of 15 cmol $m^{-2} s^{-1}$. (Sharkey and Rashke, 1981).

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LIGHTING APPLICATIONS

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