

# Semiconductor-Olefin Adducts. Photoluminescent Properties of Cadmium Sulfide and Cadmium Selenide in the Presence of Butenes

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**Abstract:** Direct evidence for adduct formation between butenes and etched, single-crystal n-CdS and n-CdSe [CdS(e)] surfaces has been obtained from photoluminescence (PL) measurements. Exposure of CdS(e) to butenes causes enhancement of the solids' band edge PL relative to a N<sub>2</sub> ambient. For 30% mixtures of the olefins in N<sub>2</sub>, the magnitude of the enhancement follows the order 1,3-butadiene > *cis*-2-butene ~ *trans*-2-butene > isobutylene ~ 1-butene and correlates with the olefin basicities, on the basis of photoionization potentials. Enhancements in PL intensity can be fit to a dead-layer model, allowing the determination of the reduction in depletion width in the semiconductor resulting from olefin exposure; depletion width reductions reach a few hundred angstroms for adducts of 1,3-butadiene with CdS(e). The PL changes were used in conjunction with the Langmuir adsorption isotherm model to yield equilibrium constants for adduct formation of 1,3-butadiene with CdS(e) of  $9 \pm 4 \text{ atm}^{-1}$  at 293 K. Surface interactions that may contribute to the observed PL changes are discussed.

The ability of irradiated semiconductors to mediate a variety of organic reactions, including the isomerization and oxidation of olefins, has aroused considerable interest.<sup>1</sup> These transformations must be crucially dependent on the binding of the molecule to the semiconductor surface. Although reaction intermediates have been studied,<sup>1</sup> direct evidence for simple olefin adducts with semiconductor surfaces has not, to our knowledge, been reported.

We have recently demonstrated that photoluminescence (PL) from semiconductors is affected by adduct formation with gaseous Lewis acids and bases: relative to a N<sub>2</sub> ambient, band edge PL from etched, single-crystal n-CdS and n-CdSe [CdS(e)] is increased in the presence of Lewis bases like amines and decreased by exposure to Lewis acids such as SO<sub>2</sub>.<sup>2</sup>

We report herein that this methodology may be extended to a family of unsaturated hydrocarbons, the butenes. Specifically, we demonstrate that exposure of CdS(e) substrates to butenes leads to PL enhancements that can be correlated with the basicities of the butenes; that the PL changes can be fit to a dead-layer model, permitting the semiconductor's depletion width to be tracked between gaseous ambients; and that the PL changes are described by a Langmuir adsorption isotherm model, allowing determination of equilibrium constants for adduct formation. The use of different etchants, 0001 and 000 $\bar{1}$  CdS(e) crystal faces, and other unsaturated hydrocarbons provides some insight into the molecular interactions underpinning the observed PL effects.

## Experimental Section

**Materials and Sample Preparation.** The following gases were used as received from Matheson: *n*-butane (95.0%); 1,3-butadiene (99.0%); *cis*-2-butene (95.0%); *trans*-2-butene (95.0%); 1-butene (99.0%); isobutylene (99.0%); ethylene (99.5%); allene (93%); acetylene (99.6%); propyne (99.0%). Nitrogen (99.5%) was obtained from Badger Welding. Impurities present in the hydrocarbons, determined by a Kratos MS25 GC/MS system, cause negligible PL changes at the concentrations present. Methanol, bromine (Fisher, 99.9%), and electronic grade HCl (Columbus Chemical) were used as received for etching. Single-crystal, vapor-grown *c* plates (10 × 10 × 1 mm) of n-CdS(e) with resistivity of ~2 Ω cm were obtained from Cleveland Crystals, Inc., Cleveland, OH, and were prepared for use by scoring and breaking into ~4 × 4 × 1 mm pieces. One of two etching procedures was then employed. In one method, samples were alternately wiped and etched (Br<sub>2</sub>/MeOH; 1:30 v/v; 5 s) until the shiny 0001 Cd-rich and matte 000 $\bar{1}$  S(e)-rich faces

were observed and then ultrasonicated in MeOH. The second etch consisted of exposure to concentrated HCl for 5 s, followed by a rinse in MeOH. Samples were edge-suspended with DUCO cement from a glass rod and left in air until use.

**Gas-Handling Apparatus.** The all-glass setup used for exposing the semiconductor to pure N<sub>2</sub> or to mixtures of the hydrocarbons in N<sub>2</sub> under flow conditions has been described.<sup>2a</sup> All such experiments were conducted at a flow rate of 100 mL/min. An apparatus permitting static measurements for adsorption isotherm experiments has also been described.<sup>2a</sup> A search for photoisomerization was conducted using an all-glass cell having a volume of 2 mL. This cell had an opening into which a CdS sample (~0.25-cm<sup>2</sup> surface area; 0001 face exposed to the cell interior), mounted on a glass stopper with DUCO cement, was placed. The glass face opposite the sample was flattened to permit excitation with minimal light scattering. By use of a Schlenk line, a butene gas was introduced into the cell at 1 atm of pressure. The CdS sample was then irradiated in the presence of the gas with 10 mW of 457.9-nm light for 10 h. After irradiation, the gas was collected by condensation in an evacuated 5-mL bulb. Aliquots of gas (0.2–0.5 mL) were taken for injection into the Kratos MS25 system. The GC was equipped with a Chrompak Model 7815 50-m × 0.32-mm porous layer open tubular (PLOT) column and a split injector. The splitter was set at 200:1 with a He pressure of 1 kg/cm<sup>2</sup>. Oven temperature was maintained at 80 °C for 1 min and then ramped to 200 °C at a rate of 20 °C/min. The mass spectrometer detector was used in full-scan mode with a cycle time of 1 scan/s. Under these conditions the butene gases are easily separated. The photolysis and analysis were repeated for each of the butene gases.

**Optical Measurements.** The He-Ne and Ar<sup>+</sup> lasers used for excitation and associated PL detection equipment have been described previously.<sup>2a</sup>

## Results and Discussion

Single-crystal, *c* plates of n-CdS(e) exhibit band edge PL at 293 K, when irradiated with ultrabandgap light. For CdS, green PL is observed ( $\lambda_{\text{max}} \sim 510 \text{ nm}$ ;  $E_g \sim 2.4 \text{ eV}$ ); for CdSe, the emission is red ( $\lambda_{\text{max}} \sim 720 \text{ nm}$ ;  $E_g \sim 1.7 \text{ eV}$ ). Exposure of the solids to a family of butenes causes an enhancement in PL intensity relative to the intensity in a N<sub>2</sub> ambient. Below we describe the

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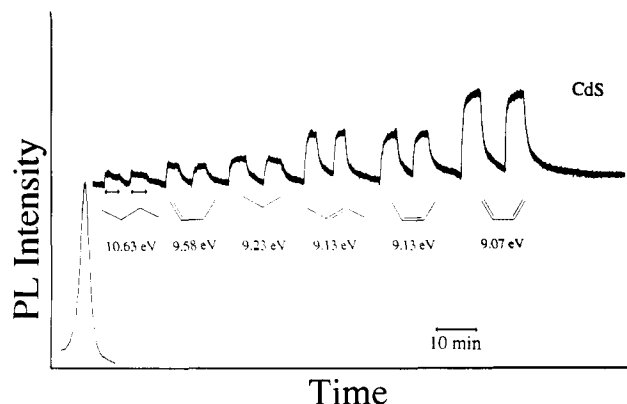
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**Figure 1.** Changes in PL intensity at 510 nm resulting from alternating exposure of an etched n-CdS sample to  $N_2$  (initial response) and the indicated gases, each present as a 30% mixture in  $N_2$ . Below each gas is its photoionization potential, taken from ref 4a. Superimposed on the plot is the original PL spectrum, obtained in  $N_2$ . Flow rates were 100 mL/min at 1 atm of pressure. The sample was excited with 457.9-nm light.

molecular dependence of this effect, its exploitation in determining semiconductor depletion widths and adduct formation constants, and the physicochemical interactions that may contribute to our observations.

**Molecular Dependence.** The majority of our studies were conducted with the shiny 0001, Cd-rich face produced by etching CdS(e) with HCl or  $Br_2/MeOH$ . After rinsing with MeOH, the CdS(e) samples were placed in a gas flow cell and irradiated with ultrabandgap light. Switching the ambient from  $N_2$  to 30% butene gas in  $N_2$  led to the reversible PL enhancements shown in Figure 1. Irrespective of the sequence of exposure, we found for a given semiconductor sample that the degree of enhancement for 30% mixtures followed the trend 1,3-butadiene > *cis*-2-butene ~ *trans*-2-butene > isobutylene ~ 1-butene > *n*-butane (the alkane's response is barely discernible above base line); pure butene gases gave the same trend. A possible complication in this set of experiments is photoisomerization, which is known to occur when oxide semiconductors such as ZnO and  $SnO_2$  are irradiated in the presence of butenes with ultraviolet light.<sup>1c</sup> Using a static system and a small volume of each butene gas, we were unable to see evidence for photoisomerization with CdS from 457.9-nm excitation; we obtain an upper limit on the photoisomerization quantum yield of  $10^{-3}$  for our experimental conditions.

With several CdS(e) samples we examined the trend in butene-induced PL response with both the 0001 and the more weakly emissive, opposing S(e)-rich, 000 $\bar{1}$  face. Within experimental error the order of the responses observed for the two faces was identical. Similarly, the use of aqueous HCl or  $Br_2/MeOH$  as an etchant produced the same trends in butene-induced PL response.

The direction of the PL change is indicative of a negative shift in the work function of the semiconductor upon exposure to the alkene, consistent with the notion that these species are serving as Lewis bases.<sup>2a,3</sup> The magnitude of the PL enhancements correlates with the basicities of the butenes, as gauged by the photoionization potentials (IPs) shown in Figure 1.<sup>4</sup> The correlation depicted in Figure 1 prompted us to examine several other unsaturated hydrocarbons. Using the 0001, Cd-rich face of CdS(e) samples, we found no PL response relative to  $N_2$  (<3% change, within our experimental error) with ethylene, which has an IP (10.5 eV) in excess of those of the butenes. Allene ( $C_3H_4$ ) with an IP of 9.6 eV<sup>4b</sup> shows about a 15% increase in PL intensity (457.9-nm excitation), close to the butene correlation.

**Table I.** Dead-Layer Analysis of CdS(e) PL Properties in Butene Ambients<sup>a</sup>

solid	butene <sup>b</sup>	$\lambda_{ex}$ , <sup>c</sup> nm	$\alpha^{-1}$ , <sup>d</sup> Å	PL ratio <sup>e</sup>	$\Delta D$ , <sup>f</sup> Å	
CdSe	1,3-diene	457.9	570	1.31	130	
		514.5	740	1.22	130	
		632.8	1500	1.11	130	
CdS	<i>cis</i> -2	457.9	1100	1.30	250	
		CdSe	457.9	570	1.21	90
		CdSe	514.5	740	1.15	90
		632.8	1500	1.07	90	
CdS		457.9	1100	1.15	130	

<sup>a</sup> Analysis of olefin-induced changes in band edge PL intensity of an etched ( $Br_2/MeOH$ ; 0001 face) CdS and CdSe sample exposed to the indicated gases (30% mixtures in  $N_2$ ). <sup>b</sup> Data are shown for the two butenes that gave sufficiently large PL responses to permit meaningful dead-layer calculations. Data for *trans*-2-butene are virtually identical to those shown for the *cis* isomer. <sup>c</sup> Excitation wavelength used in PL experiments. <sup>d</sup> Optical penetration depth of the exciting wavelength in the preceding column, taken as the reciprocal of the absorptivity.<sup>6,7</sup> <sup>e</sup> Ratio of PL intensity in the indicated ambient (30% olefin in  $N_2$ ) to that in pure  $N_2$ , both at a pressure of 1 atm. <sup>f</sup> Contraction in dead-layer thickness in passing from  $N_2$  to the indicated gas, calculated with eq 1; corrections for self-absorption ( $\beta = 1.2 \times 10^4$  cm<sup>-1</sup> for CdSe;  $5.5 \times 10^3$  cm<sup>-1</sup> for CdS) were estimated from data in ref 6 and 7.

The use of two alkynes, acetylene and propyne, resulted in PL enhancements of ~10% and 20%, respectively (457.9-nm excitation of CdS), relative to  $N_2$ ; the corresponding IP values are 11.4 and 10.4 eV. The alkyne PL response does increase with a reduction in IP, but the magnitude of the alkyne response is larger than expected based on extrapolation of the butene data. These findings underscore the fact that IP is not the sole factor contributing to PL response and that its use as a predictor of relative PL intensity is best made for a family of structurally and electronically related compounds.

**Depletion Widths.** The PL data for n-CdSe are well fit by a dead-layer model, which assumes that electron-hole pairs formed within a distance on the order of the depletion width do not contribute to PL. Neglecting changes in surface recombination velocity,<sup>2a,5</sup> eq 1 gives the quantitative form of the model, where

$$PL_1/PL_2 = \exp(-\alpha'\Delta D) \quad (1)$$

$PL_1$  and  $PL_2$  correspond to the PL intensities in  $N_2$  and in the olefin ambient, respectively,  $\alpha' = (\alpha + \beta)$  is the absorptivity of the solid, corrected for self-absorption effects, and  $\Delta D$  is the reduction in dead-layer thickness (equated with the reduction in depletion width) in passing from the  $N_2$  to olefin ambients. Table I shows that excellent agreement with the model was found for CdSe using several interrogating wavelengths whose absorptivities<sup>2a,6</sup> span a factor of ~3: for one sample that typifies our results, consistent values for  $\Delta D$  of ~130 Å with 1,3-butadiene and ~90 Å with *cis*-2-butene were observed. A smaller range of absorptivities is experimentally accessible for CdS; if we assume that the dead-layer model applies, excitation at 457.9 nm leads to a value for  $\Delta D$  of ~250 Å with 1,3-butadiene.<sup>7</sup>

**Adduct Formation Constants.** Using a static system,<sup>2a</sup> we constructed adsorption isotherms at 293 K for the most responsive adducts, 1,3-butadiene on 0001 CdS(e) surfaces, by plotting the fractional surface coverage  $\theta$  (assumed to equal the fractional PL change<sup>2a</sup>) vs butene partial pressure  $P$ , Figure 2. The expression for the isotherm contains the adduct equilibrium constant  $K$  (eq 2). Double-reciprocal plots of  $\theta^{-1}$  vs  $P^{-1}$ , shown in the inset of

$$\theta = KP/(1 + KP) \quad \text{or} \quad \theta^{-1} = 1 + (KP)^{-1} \quad (2)$$

Figure 2, are linear and permit  $K$  to be extracted from the reciprocal of the slope. We find  $K$  to be  $9 \pm 4$  atm<sup>-1</sup> for 1,3-bu-

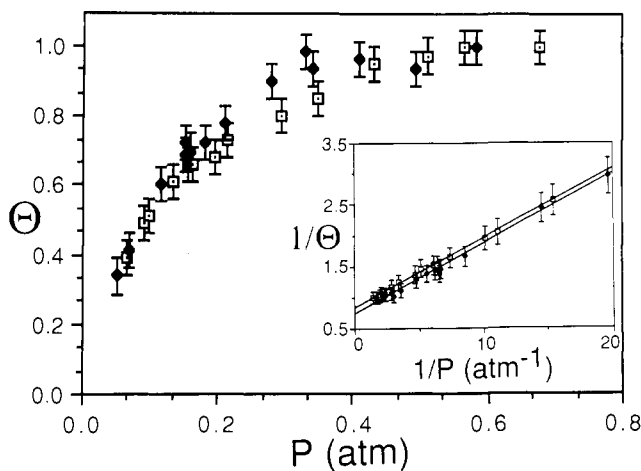
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**Figure 2.** Fractional surface coverage  $\theta$ , assumed to equal the fractional change in PL intensity, as a function of the partial pressure of 1,3-butadiene for etched single-crystal *n*-CdS (diamonds) and *n*-CdSe (squares) substrates; data were taken in random order for each semiconductor. The inset presents these same data in a double-reciprocal plot; the lines shown are least-squares best fits to the data and lead to adduct formation constants (eq 2) of  $8.8 \pm 0.2$  and  $8.9 \pm 0.2$  atm<sup>-1</sup> for CdS and CdSe, respectively, at 293 K.

tadiene on a number of CdS(e) substrates.

It is noteworthy that the Langmuir model has been successfully applied to a number of solution–semiconductor interfaces involving adsorption of halides, amines, and dithiocarbamates.<sup>8</sup> A key assumption of the Langmuir model, that the adsorbates are noninteracting, appears to be satisfied for this group of semiconductor-derived interfaces.

**Surface Interactions.** The aforementioned results raise the issue of the specific chemical interactions that are responsible for the butene-induced PL enhancements. As noted above, the direction of the PL change is consistent with binding a Lewis base to the semiconductor surface, and the magnitude of the PL enhancement correlates with IP, a basicity measure for the butenes. For atomically clean CdS(e) samples, surface Cd<sup>2+</sup> sites represent possible binding positions of Lewis acidity. While there is little precedent for Cd<sup>2+</sup>–olefin complexes, a substantial body of literature exists describing complexes prepared from olefins and the

isoelectronic Ag<sup>+</sup> ion.<sup>9</sup> However, if the Cd<sup>2+</sup>–olefin interaction is dominant, it is surprising that we see little dependence on the choice of CdS vs CdSe substrate: our expectation was that surrounding Cd<sup>2+</sup> with the more electronegative sulfide would enhance its acidity, yet we see comparable adduct formation constants. Similarly, the insensitivity to 0001 and 000 $\bar{1}$  crystal faces (with either etchant employed), as judged by the same order of PL response to the butenes, indicates that the type of site(s) needed for butene coordination is present on both faces.

While the independence of PL response on chalcogen and on crystal face may just reflect an intrinsic insensitivity to these chemical environments, it may also signal the presence of other species on these ambiently prepared surfaces. The preparative conditions that we have employed can leave halide, water, and/or methanol on the surface, for example, and these compounds or species derived therefrom may play important roles in adduct formation: surface protons, for example, could provide Lewis acidic sites.

It is worth emphasizing that the butene–CdS(e) adducts are weak and easily dissociated at room temperature. We have now seen semiconductor–gas interactions ranging from that of CdS(e) with ethylene, which showed no response, to butenes and other unsaturated hydrocarbons—acetylene, propyne, and allene—that do have sufficient  $\pi$ -electron density to engage in adduct formation. Even stronger PL responses were found with amines, which are yet stronger bases with lower IPs.<sup>4a</sup> As these and related equilibria, including adduct formation at the semiconductor–solution interface,<sup>8</sup> are studied, we should be able to develop a better understanding of the steric and electronic interactions that govern them.

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**Registry No.** CdS, 1306-23-6; CdSe, 1306-24-7; *n*-butane, 106-97-8; 1,3-butadiene, 106-99-0; *cis*-2-butene, 590-18-1; *trans*-2-butene, 624-64-6; 1-butene, 106-98-9; isobutylene, 115-11-7; ethylene, 74-85-1; allene, 463-49-0; acetylene, 74-86-2; propyne, 74-99-7.

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