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First Observation of Bistability in Luminescence

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Bistabilities in transmission and reflection of thin (10μm) CdS films are investigated using the 514.5nm Ar^+-laser line in the temperature range 80-150K. During the experiments the following discovery is made: The loops of bistabilities measured under the configuration for reflection are drastically increased by putting edge filters, which are transparent in the red region of the spectrum (e.g. RG 780), in the reflected beam. Hence, not the bistability of the reflected beam but the lower energetic bistable light emission of the thin CdS film is measured.

Nonlinearities of semiconductors are a facinating subject from both points of view: basic research and technical applications.[1,2] Thin undoped CdS layers on pyrex excited with the 514.5nm Ar^+-line exhibit considerable optical bistable and nonlinear features in transmission,[3-6] photocurrent[5-9] and reflection.[10] This series is now completed by the first observation of bistability in luminescnence. It is noteworthy that the bistability in luminescnence, especially in the range of the near infrared (λ>780nm), is a priori not directly related to the mentioned bistabilities in transmission and photocurrent which underlie a thermo-optical shrinkage of the fundamental absorption edge.[9] Moreover, the reflection of thin CdS layers exhibits unexpected complex features as self-induced oscillations.[10] One can be very curious about the future results of nonlinear and bistable features in reflection and luminescence of thin CdS films, which are hardly known up to now.

The influence of doping on the bistable features of thin CdS films is unknown. We have chosen copper as dopant since CdS:Cu is already known to exhibit interesting photoluminescence and photoconductivity properties.[11] In particular, the samples investigated were prepared by reactive spray deposition[5,12,13] on pyrex with 10^{-7}M/l Cu_2^+ in the solvent. The investigations concerning bistabilites were performed with the experimental arrangement desecribed in detail in ref. 7. The dependence of reflection and transmission on temperature at 514.5nm was measured with a halogen lamp and a monochromator applying lock-in technique.

Fig. 1 shows the result of a coincident measurement of transmission and reflection at an ambient temperature (T_a) of 150K. The bistable switch of the transmission is explained by Fig.2, which shows the measured (solid lines) and calculated (broken lines) dependences of the transmission ($Tr(T)$) and reflection ($Re(T)$) on temperature. The nonlinearity of ($Tr(T)$) is the origin of the bistability in transmission. Two tangents on $Tr(T)$, which start at the co-ordinates T_a and $1-R(T_a)$ (150K, 0.7), define the bistable switch down (a→b) and the bistable switch up (c→d), respectively.[7,14] However, what's about the reflection? $R(T)$ stays in the considered temperature range (80-350K) almost constant and shows in the temperature range where the bistable switch in the transmission occurs a

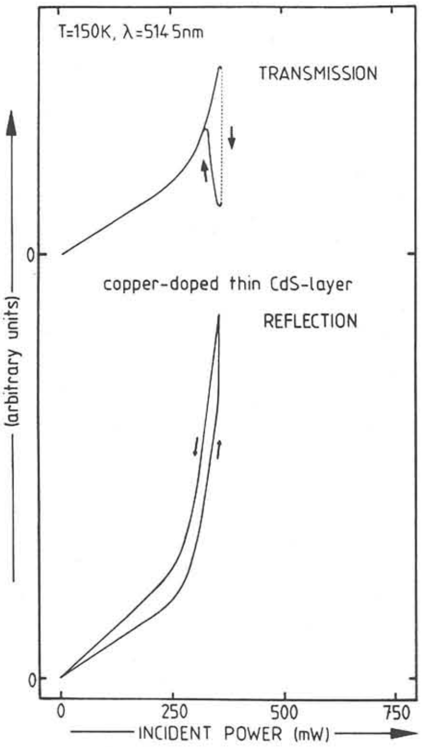

Fig.1: Coincident measurement of transmission and reflection of a thin (10µm) CdS:Cu film at 150K. The transmission shows in contrast to the reflection a bistable loop.

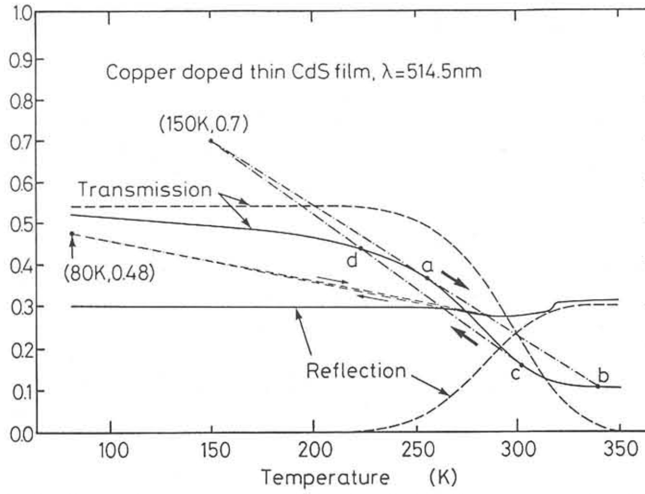

Fig.2: The measured (solid lines) and the calculated (broken lines) dependences of the transmission and reflection on temperature of a copper doped thin (10µm) CdS film at 514.5nm. The bistable switch of the transmission is defined by the two tangents (broken-dotted lines) starting at the operating point (150K, 0.7). The switch down occurs between the points a and b and the switch up between c and d. The solution for the bistability in reflection (see Fig.3) is indicated by two tangents (broken-dotted lines) starting at (80K, 0.48).

weak decrease, which is not in agreement with the measurement of Fig.1 because during the bistablity of transmission only an increase in the reflection takes place. Further, the bistable switching time of the reflection was observed to be slower than the switching time of the transmission. Hence, the behavior of the reflection in Fig.1 cannot be explaind by Fig.2. Moreover, it is very noteworthy that the standard theory which is expressed by[15]

$$Re(T)=R\,\frac{1-exp(-2\alpha(T)d)}{1-R^2exp(-2\alpha(T)d)} \qquad (1)$$

and

$$Tr\,(T)=\frac{(1-R)^2exp(-\alpha(T)d)}{1-R^2exp(-2\alpha(T)d)} \qquad (2)$$

describes $Tr(T)$ quite fair but not $Re(T)$; R (=0.3) is the reflection coefficient, α is the absorption coefficient and d (=10µm) is the thickness of the sample. $\alpha(T)$ is given by[7]

$$\alpha(T)=A_0\sqrt{\frac{kT}{2\sigma}}\;exp\left\{\frac{\sigma E}{kT}-\frac{\sigma E_g(T)}{kT}-\frac{1}{2}\right\} \qquad (3)$$

where $A_0=2\times10^5\,cm^{-1}(eV)^{-1/2}$, k is Boltzmann's constant, σ is a dimensionless phenomenological parameter ≤2.17 describing the Urbach tail[16,17] and E is the energy of the incident light beam (=2.41eV). The dependence of the gap on the temperature ($E_g(T)$) is expressed by

$$E_g(T)=E_{gi}-(T-T_i)\left\{\frac{\Delta E_g}{\Delta T}\right\} \qquad (4)$$

where $E_{gi}=E_g(300K)=2.44eV$,[6-8] $T_i=300K$ and $\Delta E_g/\Delta T=4.1\times10^{-4}eVK^{-1}$.[18]

Fig. 3 shows the bistable loop of the reflection at 80K. Since tangents on $Re(T)$ can be found from the operating point for the reflection ((80K, 0.48), see Fig.2) the observation of bistability becomes possible. The contrast of the loop (7%) is in agreement with the decrease of 7% of $Re(T)$ between 270K and 286K where the switch in bistability occurs (see the tangents on $Re(T)$ in Fig.2). The loop contrast can be considerably increased (63%) if edge filters, which are transparent in the red part of the spectrum, were putted in the reflected beam. Thus, the radiative light

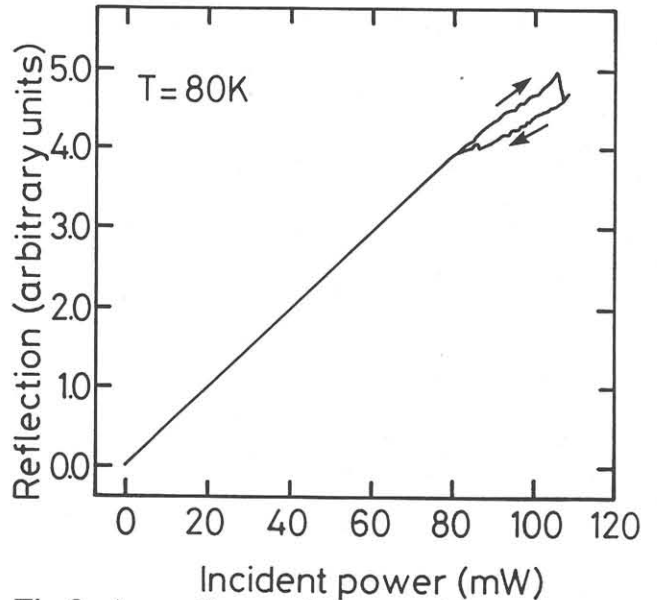

Fig.3: According to the expection of Fig.2, the sample exhibits only a weak bistability in reflection at 80K.

emission with λ>780nm is measured. The result is shown in Fig.4, which represents the first observation of bistability in luminescence.

It is worthwhile to stress at this point that the bistability of luminescence cannot be concluded straightforeward from common interpretations of thermo-optical bistabilities (see refs. 7,8,14) since the thermo-optical shrinkage of Urbach's tail around 2.41eV not necessarily influences transitions at 1.55eV where the maximum of the luminescence takes place. However, we have pointed out that the efficiency of the luminescence around 1.55eV is six times higher at 80K than at 300K. Hence, the clock-wise bistable loop of the luminescence is caused by the temperature dependece of the luminescence at 1.55eV. Consequently, the bistability of luminescence is a thermally induced electronic effect. In other words, slow (≥μs)[19] thermal switching times of so-called laser induced optical devices (LIODs) can be improved probably since the switch of the luminescence depends not only on the thermal relaxation time but also on the radiative recombination time. Currently, the speed of switching is under investigation.

As already mentioned above the reflection of thin CdS films exhibits some puzzling properties. The most striking point is the large disagreement between eq.(1) and *Re(T)* of Fig.2. We have pointed out, that the surface life time (τ_S) of thin CdS films depends

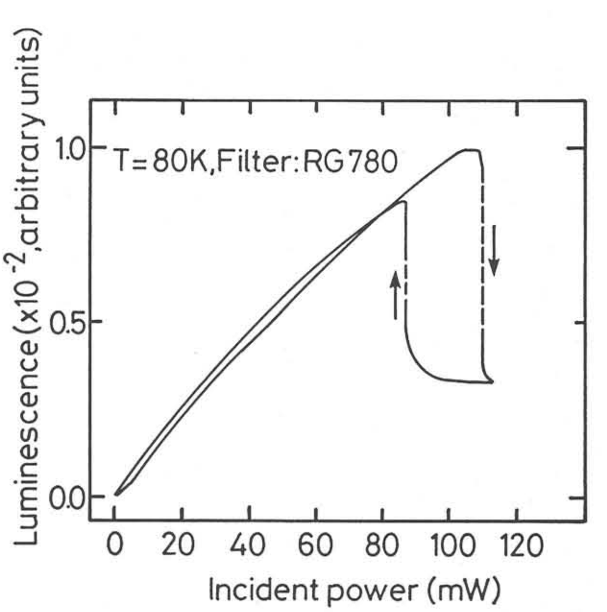

Fig.4: The repetition of the measurement of Fig.3 putting the filter RG 780 in the reflected beam. A completely different behavior as in Fig.3 is observed. This is the first realization of a bistable switch in luminescence.

strongly on temperature. In particular, τ_S decreases from the ms-range at 80K to the μs-range at 300K. Therefore, one possibility to explain the discrepancy between theory and expriment is the consideration of the dependence of the free carrier density on temperature. A decrease of the recombination rate at the surface at low temperatures increases the free carrier density and thus the probability of electron-photon scattering, which leads to an increase of the reflection.

In conclusion, we have measured for the first time a bistable loop in luminescence. We want to point out that the presented discovery is very interesting for an all-optical material characterization of the electronic properties of semiconductors (e.g. impurity concentration, steepness of the absorption edge, etc.) because the loop contrast is very sensitive to the filter (loop contrasts: OG 590 13%, RG 630 15%, RG 715 49%), which is putted in the reflected beam. Finally, the bistability of luminescence opens various new perspectives to devise hybrid interfaces since the bistability of luminescence can be also induced by an electrical bias in combination with a constant optical one. Hence, a LIOD driven in the hybrid luminescent mode can convert electrical signals, e.g. the output of a TTL logic, into photonic pulses for data transfers via fibers.

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