GEM TN-92-149
Rev. A
CALT-68-1812

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CALT-68-1812
DOE RESEARCH AND
DEVELOPMENT REPORT
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ON OPTICAL BLEACHING OF BARIUM FLUORIDE CRYSTALS[1]

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Abstract

This report presents results on optical bleaching for 25 cm long BaF_2 crystals to be used in constructing a BaF_2 calorimeter at the SSC. A practical scenario of implementing optical bleaching *in situ* and the requirements on the light sources used to bleach the entire GEM BaF_2 calorimeter are presented.

1 Introduction

Barium fluoride (BaF_2) crystals were considered by the GEM Collaboration, to be used in constructing a precision electromagnetic calorimeter at the SSC [1]. The key issue of using this crystal at the SSC is its radiation resistance [2]. An Expert Panel was assigned by the SSC laboratory to review the radiation damage problem of BaF_2. The Panel met in December 1991 and again in January 1992 following a site visit to the Shanghai Institute of Ceramics (SIC) and Beijing Glass Research Institute (BGRI) by selected Panel members and the GEM Spokesmen. The principal conclusion of the Panel's February 1992 report is "there is no

[1]**Work supported in part by U.S. Department of Energy Contract No.DE-FG03-92-ER40701.**

apparent fundamental reason why BaF_2 can not be made radiation hard" [3].

The conclusion from the BaF_2 Panel is based upon existing data obtained by that time. Some highlights are summarized below:

- The BaF_2 radiation damage caused by photons shows clear saturation. Both transmittance and light output measured after irradiation do not degrade further after initial dosage of a few tens kRad to 100 kRad, depending on the quality of the BaF_2 crystals; (Figures 12 and 14 of [2])
- There is no permanent damage caused by either photons or neutrons. All damage recovers in full after an annealing at 500°C for three hours; (Figures 12 and 17 of [2])
- There is very slow spontaneous annealing of the transmittance at 220 nm of BaF_2 under room temperature measured up to 68 days after 1 MRad irradiation; (Figures 15 and 16 of [2])
- The radiation damage of BaF_2 has no dose rate dependence; (Figure 17 of [2])
- There is evidence that the damage of BaF_2 is caused by formation of color centers, which cause self-absorption of the scintillation light as it is transmitted through the crystal. There is no apparent damage to the scintillation mechanism itself, so that the intrinsic scintillation light yield by the crystal is not affected (Section 5.4 of [2]).
- Large size (20-25 cm long) BaF_2 crystals produced by SIC in December 1991 have considerably better radiation resistance than the crystals from previous batches. The transmittance of two 20 cm long crystals is ~50% at 220 nm after 1 MRad irradiation which corresponds to a light attenuation length (LAL) [5] of around 34 cm. (Figures 18 and 19 of [2])

The specification on BaF_2's radiation resistance, proposed by the BaF_2 Collaboration, is the light attenuation length of longer than 95 cm for 25 cm long crystals after 1 MRad irradiation [2,5]. This specification was based upon a study of the influence of the light attenuation length on crystal's light response uniformity, and thus on the energy resolution [2]. It was also assumed that a stable high precision crystal calorimeter could be built by using pre-irradiated crystals of this quality. This stability is due to the saturation of the radiation damage, and the very slow spontaneous recovery rate of the transmittance at the wavelength of BaF_2's fast scintillation component (220 nm), at room temperature.

After six months, the Panel had its final meeting in early August, 1992. The R&D progress up to the meeting date was evaluated. The progress in radiation resistance quality of production BaF_2 crystals, however, did not match the specification of the BaF_2 Collaboration. The main conclusions of Panel's August meeting are [4]:

- With the knowledge presently available, preirradiation is not a viable solution to the radiation damage problem of BaF_2;
- The only solution is to use annealing of the crystal by exposure to light *in situ*. Such a method could make a calorimeter satisfying GEM's specifications using present production crystals.

Following Panel's recommendation, an extensive R&D was carried out at Caltech. This report presents result of optical bleaching for 25 cm long BaF_2 crystals produced by SIC. A practical scenario of implementing optical bleaching *in situ* and the requirements on the light sources used to bleach the entire GEM BaF_2 calorimeter are presented.

2 Experiment

2.1 Samples

Two 25 cm long BaF_2 crystals produced by SIC were tested. Crystal SIC302 was produced at the end of 1991 with a light attenuation length of 34 cm after 1 MRad irradiation. The other sample SIC402 is the latest crystal produced by SIC which has a light attenuation length of 41 cm after 1 Mrad irradiation. Table 1 lists the dimension, transmittance (T) at 220 nm and corresponding light attenuation length (λ) for these four crystals, where the subscript 0 and 1M refer to before and after 1 Mrad ^{60}Co γ-ray irradiation. The progress in radiation resistance of BaF_2 crystals produced by SIC is clearly shown in the increase of T_{1M} and λ_{1M}.

Note, the sample SIC402 was irradiated to 1 MRad by using a ^{60}Co source at SIC, and was consequently bleached to a saturation by using a high pressure mercury lamp whose irradiance spectrum covers 270 to 440 nm [6]. Before the first irradiation, the transmittance of SIC402 was measured at SIC to be 86% [6]. It is clear that the optical bleaching by using mercury lamp did not remove all color centers created by the irradiation.

Table 1: Properties of Four SIC Samples

Sample	Dimension (cm)	T_0 (%)	λ_0 (cm)	T_{1M} (%)	λ_{1M} (cm)
SIC302	$3^2 \times 25 \times 4^2$	87.2	779	43.3	34
SIC402	$3.6^2 \times 25 \times 4.6^2$	78.4	181	48.6	41

2.2 Transmittance Measurement

The transmittance of 25 cm long BaF_2 crystals was measured by using a Hitachi U-3210 UV/Visible spectrophotometer which is equipped with double beam, double monochromator and a large sample compartment with custom Halon coated integrating sphere. The systematic uncertainty in repeated measurements of transmittance is around 0.2% for 25 cm long BaF_2 crystals.

2.3 Bleaching Setup

The light from a monochromator (BAUSCH & LOMB, Grating 1200 Grove/mm) was shot through the large end of the tapered 25 cm long BaF_2 crystal. To investigate the optical bleaching cross-section, no reflector was placed at any surface of the crystal. The entire bleaching setup was kept in dark. The monochromator was set to have a bandwidth around 10 nm with a rectangular light spot with a dimension of 0.8" (height) × 1" (width).

Light with different wavelengths was used in the experiment. The crystal was illuminated with the light, and the transmittance of the crystal was measured frequently until a saturated value was reached. In our first measurement, the same procedure was repeated for red light (700 nm), green light (500 nm), blue light (400 nm) and UV light (300 nm).

2.4 Calibration of the Light Intensity

The calibration of the light intensity was carried out by using a Hamamatsu Si-diode of 1×1 cm^2 with known quantum efficiency. Apertures with different diameter (5, 7.5 and 10 mm) were used to verify the uniformity of the light intensity from the monochromator. It was found that the photo-current is proportional to the area of the aperture to within 5% for the cases of 5 and 7.5 mm. This indicates that the light intensity in this area has a good uniformity.

Table 2 lists the intensity of the light (I) and the corresponding photon flux (F), at the position where the light entering the crystal, for wavelengths of 300, 400, 500 and 700 nm. For convenience, the photon energy, the integrated energy density of the light per hour (P) and the integrated photon density per hour (N) are also listed.

Table 2: Light Intensity of Monochromator

Wavelength (nm)	300	400	500	700
Photon Energy (eV)	4.1	3.1	2.5	1.8
I (mW/cm^2)	0.21	0.85	1.5	1.0
F (10^{15} $photon/cm^2/s$)	0.32	1.7	3.8	3.5
P ($J/cm^2/hour$)	0.76	3.1	5.4	3.6
N (10^{18} $photon/cm^2/hour$)	1.2	6.1	13.7	12.6

3 The Wavelength Dependence

Sample SIC302 was first illuminated with a red light (700 nm). After 30 hours of illumination, the light attenuation length saturated at around 100 cm. The wavelength of the bleaching light then was changed to 500 nm — the light attenuation length changed very little in 5 hours. It was further changed to 400 nm. After another 10 hours, the light attenuation length saturates again at 180 cm. The light finally changed to 300 nm, the light attenuation length was saturated after around 10 hours.

Table 3 lists the measured transmittance (T) at 220 nm, corresponding light attenuation length (λ), color center density ($1/\lambda$) and color center density normalized to after 1 MRad irradiation (λ_{1M}/λ). Figure 1 shows the transmittance spectra measured. The transmittance at 220 nm (T), its corresponding light attenuation length (λ) and color center density ($1/\lambda$) are plotted as a function of time in Figure 2.

This result indicates that there is a wavelength threshold of bleaching light below which a different type of color center in SIC crystal can be effectively bleached. This threshold is between 400 to 500 nm. In the next study, we will determine the threshold, and we can use the bleaching light source with wave length of just a little shorter than this threshold, but longer than 400 nm. By doing so, the effect to our solar blind phototube will be reduced to a minimum.

By using the calibration in Table 2, this data also show that 108 J/cm^2 of 700 nm light plus 31 J/cm^2 of 400 nm light are required to bleach the crystal to 180 cm. The time needed to bleach the crystal to the mid point, defined as 0.5/(saturated LAL), is 4.5 hours for 700 nm and 1 hour for 400 nm. The corresponding energy density needed is 16 J/cm^2 and 3.1 J/cm^2 respectively for light of 700 and 400 nm.

Table 3: Bleach SIC302 with Different Wavelengths

Time (hours)	T(%)	λ (cm)	$1/\lambda$ (1/m)	λ_{1M}/λ
Before Irradiation				
	87.2	779	0.13	
1 MRad Irradiation by ^{60}Co γ-ray				
	43.5	34.5	2.9	1.00
Under 700 nm Red Light				
0.	43.5	34.5	2.9	1.00
2.	47.6	39.3	2.5	0.88
4.5	54.6	50.1	2.0	0.69
14.5	63.6	72.2	1.4	0.45
24.	67.1	85.3	1.2	0.40
30.	70.	99.6	1.0	0.35
35.	69.5	97.1	1.0	0.35
Under 500 nm Green Light				
35.5	71.	105.6	0.95	0.33
37.	71.2	106.9	0.94	0.32
39.5	71.3	107.5	0.93	0.32
43.	71.3	107.5	0.93	0.32
Under 400 nm Blue Light				
43.5	72.4	115.0	0.87	0.30
44.5	76.2	150.3	0.67	0.23
54.5	78.9	190.	0.53	0.18
64.	78.5	183.	0.55	0.19
65.	78.3	180.	0.56	0.19
Under 300 nm UV Light				
66.	79.1	194.	0.52	0.18
67.	78.7	186	0.54	0.19
75.	79.5	202	0.50	0.17
89.5	80.4	221	0.45	0.16
95.	81.1	240	0.42	0.15

4 Bleach BaF_2 Crystals with 400 nm Light

As shown in Section 3, the 400 nm light can be used for an effective optical bleaching of BaF_2 crystals. In order to determine the exact light energy density required to bleach color centers caused by 1 MRad irradiation, we re-irradiated SIC302 to 1 MRad after the test described in Section 3, and tested bleaching by using 400 nm light again.

Table 4 lists the measured transmittance (T) at 220 nm, corresponding light attenuation length (λ), color center density ($1/\lambda$) and the 400 nm bleachable color center density (D). Figure 3 shows the transmittance spectra measured. The transmittance at 220 nm (T), its corresponding light attenuation length (λ) and 400 nm bleachable color center density (D) are plotted as a function of time in Figure 4.

Table 4: Bleach SIC302 with 400 nm Light

Time (hours)	T(%)	λ (cm)	$1/\lambda$ (1/m)	D (1/m)
0.	43.3	34.2	2.92	2.37
0.5	58.7	58.6	1.71	1.16
1.0	64.6	75.5	1.32	0.777
1.5	67.9	88.9	1.13	0.578
2.5	71.8	111	0.902	0.355
4.5	74.6	133	0.750	0.203
12.0	78.5	183	0.547	0.0
13.0	78.0	175	0.572	0.025

A test with the latest 25 cm long BaF_2 crystal SIC402, which was delivered in August 1992, produced a similar result, as shown in Table 5, Figure 5 and Figure 6. In summary, both SIC302 and SIC402 have been bleached to a saturated light attenuation length of 180 cm in around 10 hours. This indicates an energy density of 31 J/cm^2 for 400 nm light, or photon density of 6.1 x 10^{19} photons/cm^2, is enough to bleach current 25 cm long crystals from saturated damage to 180 cm. Less than 1 hour is needed to reduce the bleachable color center density to half of its original value for current production crystals. which corresponds to 3 J/cm^2 or 6 $\times 10^{18}$ photons/cm^2.

Table 5: Bleach SIC402 with 400 nm Light

Time (hours)	T(%)	λ (cm)	$1/\lambda$ (1/m)	D (1/m)
0.	48.6	40.5	2.47	1.92
1.0	61.6	66.1	1.51	0.96
1.5	66.8	83.8	1.18	0.63
3.5	72.4	115	0.870	0.32
6.5	76.9	159	0.629	0.077
8.5	77.7	171	0.585	0.033
9.5	77.8	172	0.581	0.028
18.5	78.4	181	0.552	0.0

5 Color Center Dynamics: Annihilation and Creation

It is important to understand the dynamic process of the annihilation and creation of optically bleachable color centers.

5.1 Color Center Annihilation

From the data presented in Section 4, it is straight forward to mathematically formulate the process of color center annihilation. The annihilation speed is proportional to the existing bleachable color center density (D) and the light intensity used:

$$dD = -aIDdt \tag{1}$$

where a is a constant in a unit of $cm^2/mW/hour$, I is the light intensity in a unit of mW/cm^2, and t is the time in a unit of hour. Equation 1 can be solved with a solution of

$$D = D_0 \; e^{-aIt} \tag{2}$$

By using Table 5, we determined a = 0.85 $cm^2/mW/hour$.

5.2 Color Center Creation

Table 6 lists the transmittance (T) at 220 nm, corresponding light attenuation length (λ), total color center density ($1/\lambda$) and optical bleachable color center density (D) for sample SIC402. These data were obtained by reirradiate SIC402 after 1 MRad irradiation followed by a complete optical bleaching.

Table 6: Transmittance and LAL of SIC402 after Irradiation

Dosage	0 Rad	1 kRad	100 kRad	1 MRad
Transmittance (%)	78.4	63.8	49.2	48.6
λ (cm)	181	73	42	41
$1/\lambda$ (1/m)	0.55	1.4	2.4	2.5
D (1/m)	0	0.85	1.85	1.95

The creation speed of optically bleachable color center density (D) is proportional to the existing trap density (D_{all} -D) and to the radiation dose rate, where D_{all} is the total density of traps related to the optically bleachable color centers in the crystal (1.95/m for current production BaF_2 crystals from SIC).

$$dD = (D_{all} - D) \; bRdt \tag{3}$$

where b is a constant in a unit of 1/kRad, R is the radiation dose rate in a unit of kRad/hour, and t is the time in a unit of hour. Equation 3 can also be solved with a solution of

$$D = D_{all}\left(1 - e^{-bRt}\right) \quad (4)$$

By using Table 6, we determined b = 0.57 /kRad.

5.3 Color Center Dynamics

In general, annihilation and creation may exist at the same time. We have

$$dD = -aIDdt + (D_{all} - D)\, bRdt \quad (5)$$

The solution of Equation 5 is

$$D = \frac{bRD_{all}}{aI + bR}\left[1 - e^{-(aI+bR)t}\right] \quad (6)$$

For each values of I and R, an equilibrium between annihilation and creation will be established at an optical bleachable color center density of

$$D = \frac{bRD_{all}}{aI + bR} \quad (7)$$

6 A Realistic Scenario of Optical Bleaching

6.1 The Scenario

It should be noticed that the bleaching using 400 nm does not provide a complete recovery for BaF_2 crystals, i.e the light attenuation length (λ) will not recover to the status of before irradiation, or after a thermal annealing [8]. A realistic scenario of *in situ* bleaching by using 400 nm light thus includes:

- Pre-irradiation;
- Pre-bleaching; and
- *in situ* bleaching.

Note, the pre-irradiation discussed here is different to what discussed extensively by the BaF_2 Expert Panel [3,4]. The purpose of this pre-irradiation is to activate those deep color centers which can not be bleached by using 400 nm light. The detailed dosage needed for pre-irradiation should be investigated in near future.

The pre-bleaching can be carried out by illuminating naked crystals with a powerful blue lamp. This is to provide a starting light attenuation length of around 180 cm for current production BaF_2 crystals. The optical coating and light response uniformity measurement should be carried out after pre-bleaching. The crystal after this initial treatment will have a maximum light attenuation length around 180 cm and will not request a dark room for handling.

Recent Monte Carlo study by K. Shmakov [9] shows that the requirement on *in situ* bleaching should keep the light attenuation length between 110 to 180 cm. By doing so, the light response uniformity and thus the high energy resolution of BaF_2 crystal calorimeter will not be compromised.

6.2 Energy Density Required for *in situ* Bleaching

There are two possible approaches for *in situ* optical bleaching:

- bleaching when needed; and
- bleaching during run.

We discuss in details the energy density required for these two approaches in the rest of this section.

6.2.1 Bleaching when Needed

By using Equation 2, we can calculate the energy density of 400 nm light needed to bleach a BaF_2 crystal from λ_1 to λ_2:

$$I(t_2 - t_1) = \frac{\ln(D_1/D_2)}{a} = 1.12 \ln\frac{1/\lambda_1 - 0.55}{1/\lambda_2 - 0.55} \quad (8)$$

Assuming $\lambda_1 = 110$ cm and $\lambda_2 = 160$ cm, we have $I\Delta t = 6.3$ J/cm^2, where Δt = t_2 - t_1. Equation 9 can be used to calculate power needed for any working interval of the light attenuation length.

Since the sum of equivalent surface area of all crystals of GEM BaF_2 calorimeter is around 200,000 cm^2 (calculated at the middle of the crystal), 1.2 MJ is needed to bleach all crystals from 110 cm to 160 cm. This means that a light source with an effective power of 600 W would do the job in 30 minutes through 16,000 fibers to each crystal.

Note, this energy density needed will be reduced by a factor of around 3 if the crystals were wrapped with reflector to allow multiple bouncings inside the crystal.

By using Equation 4, we can calculate the value of the time interval (Δt) in which the light attenuation length degradats from λ_1 to λ_2:

$$\begin{aligned} \Delta t &= \frac{1}{bR} \ln \frac{D_{all} - D_1}{D_{all} - D_2} \\ &= \frac{1.8}{R} \ln \frac{2.5 - 1/\lambda_1}{2.5 - 1/\lambda_2} \end{aligned} \quad (9)$$

Assuming $\lambda_1 = 160$ cm and $\lambda_2 = 110$ cm, we have $\Delta t = 0.30/R$ hours. The Equation 10 thus can be used to calculate the time interval in which the BaF_2 crystal will stay in the working interval of the light attenuation length between λ_1 and λ_2, provided a radiation dose map is known.

In the worst case of $|\eta| = 2.5$ at the SSC, the dose rate is around 0.4 kRad/hour at standard luminosity. This indicates *in situ* bleaching needs to be carried out less than one hour at $\eta = 2.5$ and every 15 and 7.5 hours at $\eta = 0$ and 1. Assuming a physics run has a beam time of 8 hours at the SSC, this approach seems applicable for the BaF_2 barrel constructed with current production crystals at the standard SSC luminosity, but has limitation for end caps and high luminosity, i.e. 10^{34} cm^{-2} s^{-1}. BaF_2 crystals with better quality, i.e. low total trap density D_{all} and b are needed, if this approach is to be used *in situ*.

Note, if a powerful laser with short pulse is used, this approach may be adequate for current production BaF_2 crystals, even at high luminosity. Some eximer laser, e.g. 351 nm laser with xenon fluoride gas should be investigated.

6.2.2 Bleaching during Run

An alternative approach is to implement the bleaching light constantly on crystals during run. Because of the solar blindness, the proposed readout device for BaF_2 crystals would not see the bleaching light at 400 nm. In this approach, crystals are assumes to work at a particular light attenuation length, i.e. at **a working point** (λ_w), which is the equilibrium point described in Equation 7.

By using Equation 7, we can calculate the intensity of 400 nm light needed to compensate the radiation dose *in situ*, so that a stable light attenuation length (λ_w) can be maintained.

$$I = \frac{bR\,(D_{all} - D_w)}{aD_W} = 0.67R\,\frac{2.5 - 1/\lambda_w}{1/\lambda_w - 0.55} \tag{10}$$

Assuming the applied light intensity is a factor of k of the value defined by Equation 11, the real light attenuation length can be calculated by using Equation 7.

$$D = \frac{D_{all}}{1 + k(D_{all}/D_w - 1)} \tag{11}$$

For current production BaF_2 crystals and the defined working light attenuation length of 150 cm, we have the real light attenuation length of

$$1/\lambda_{real} = \frac{1.95}{1 + 15.3k} + 0.55 \tag{12}$$

The real working light attenuation length can be calculated as 169 cm for k = 3 and 111 cm for k = 0.3. It is thus clear that the deviation of the intensity of the bleaching light will not compromise effective bleaching. By using a UV monitoring system which is a standard in any crystal calorimeter, a simple feedback can be established to adjust the annealing light intensity, and thus to keep crystals at $\lambda_w =$ 150 cm. The high resolution of BaF_2 crystal calorimeter thus could be maintained.

Assuming $\lambda_w = 150$ cm, the required light intensity is 10.5 R mW/cm^2, where R is the dose rate in unit of kRad/hour. The required light intensity thus is proportional to the dose rate and is also related to light attenuation length of working point. Table 7 lists the dose rate and the required light intensity as a function of rapidity for GEM BaF_2 calorimeter.

Table 7: Light Intensity Needed to Maintain BaF_2 at $\lambda = 150$ cm

$\|\eta\|$	0	1	2.5
Dose Rate (kRad/hour)	0.02	0.04	0.4
I (mW/cm^2)	0.21	0.42	4.2

In this approach, the maximum total power required for barrel is around 52 W, while the two endcaps need 100 W. An effective light source of 150 W thus will be enough to maintain 150 cm light attenuation length for entire BaF_2 calorimeter. As discussed in Section 6.2.1, this intensity can be reduced by a factor of around 3, if the multi-bouncing between reflectors were taking into account.

6.3 Implementation of Optical Bleaching through Fibers

The bleaching light can be introduced to the crystal through an optical fiber. An 800 W average power can be transmitted through a 1 mm fiber [7]. This corresponds to 12.5 W for a 125 μm fiber, which greatly exceeds the power needed in either approaches discussed in this section. From Table 7, we conclude that an 125 μm fiber can accommodate the power needed at $\eta = 2.5$, if the "bleaching during run" approach is chosen. This is true even at high luminosity of 10^{34} cm^{-2} s^{-1}.

A detailed design on transferring 400 nm light to BaF_2 crystals through optical fibers has been started, and the first indication is no obvious technical difficulty in implementing the optical fiber.

7 Conclusion

We have studied optical bleaching of current production quality BaF_2 crystals by using a monochromator with well calibrated light intensity. The study shows a BaF_2 calorimeter can be built with current production crystals from China. With an effective 150 W light source, the entire BaF_2 calorimeter can be set to work at

150 cm light attenuation length. The key issue of radiation damage problem of BaF_2 crystals thus is solved.

The main conclusions of this study are:

- Light of 400 nm wavelength was found to be more effective than the 500 nm light in optical bleaching of BaF_2 crystals;
- By using 400 nm light, the saturated light attenuation length is found to be around 180 cm for two current production BaF_2 crystals;
- A maximum of effective 150 W of optical power at 400 nm is needed to bleach all BaF_2 crystals in GEM calorimeter during run at the standard SSC luminosity, and to keep the light attenuation length of all BaF_2 crystals at around 150 cm;
- A change of light intensity by a factor of 10 causes light attenuation length changes from 110 to 170 cm;
- By using a UV monitoring system, a simple feedback can be established to adjust the annealing light intensity, and thus to keep crystals at working light attenuation length of λ_w = 150 cm. The high energy resolution of the BaF_2 calorimeter thus will not be compromised.
- By using 400 nm light, 6.3 J/cm^2 is needed to bleach the crystal from λ = 110 cm to 160 cm. To completely bleach the whole GEM BaF_2 crystal calorimeter, the total energy needed is 1.2 MJ , which can be accommodated by an effective 700 W light source in 30 minutes;
- Taking into account of multi-bouncings of the bleaching light inside the crystals, all powers and energies reported in this report are expected to be reduced by a factor of around 3;
- Further improvement of crystal quality, i.e. reducing D_{all} would certainly help to reduce the requirement on the power of the light source.

8 Acknowledgement

The authors wish to thank Prof. Z.W. Yin and P.J. Li for providing BaF_2 sample for this work, and Drs. H. Kobrak, C. Wuest, Y. Kamyshkov and J. Branson for many useful discussions.

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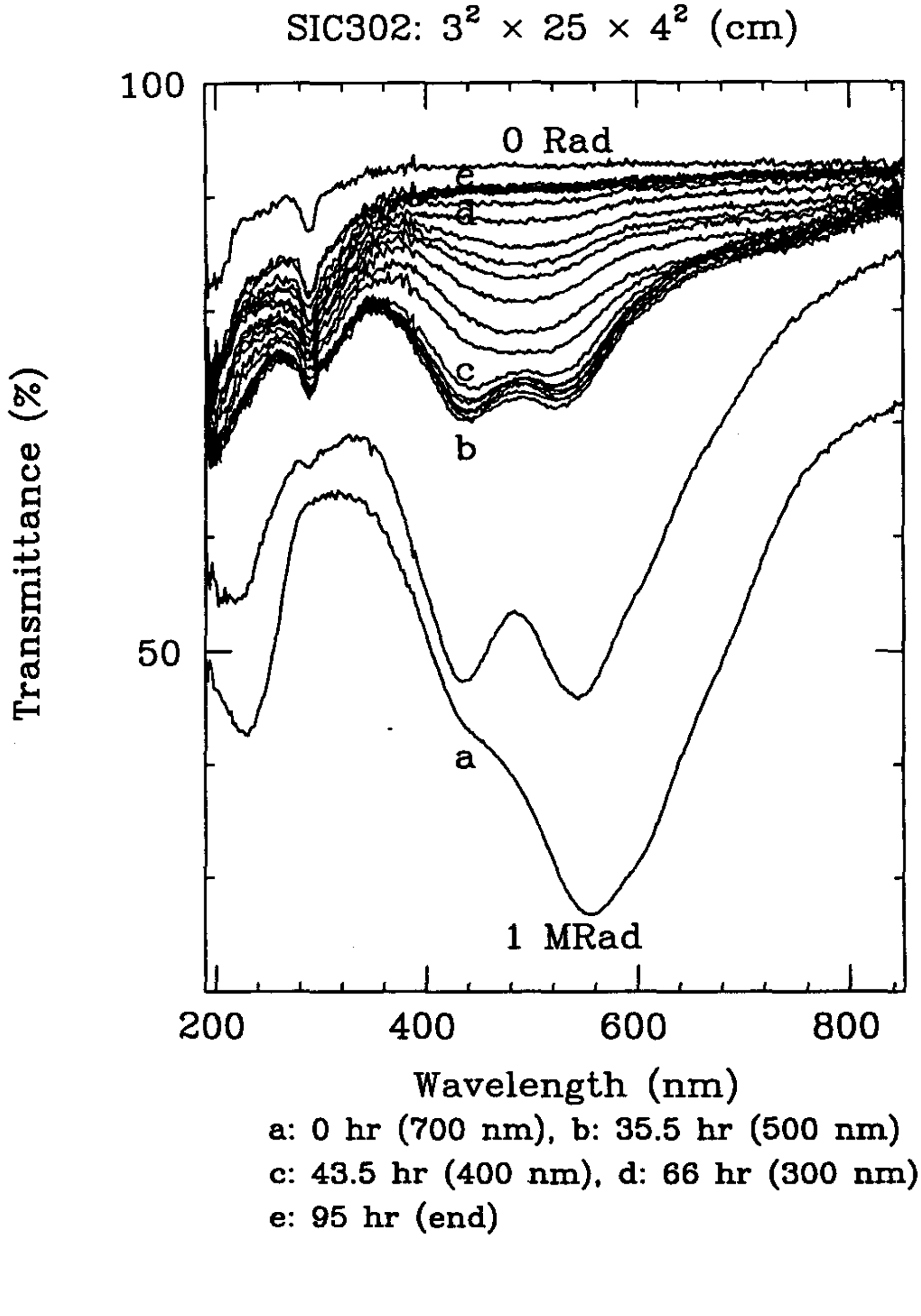

Figure 1: Transmittance of SIC302 are plotted as a function of wavelength under optical bleaching by light of different wavelengths.

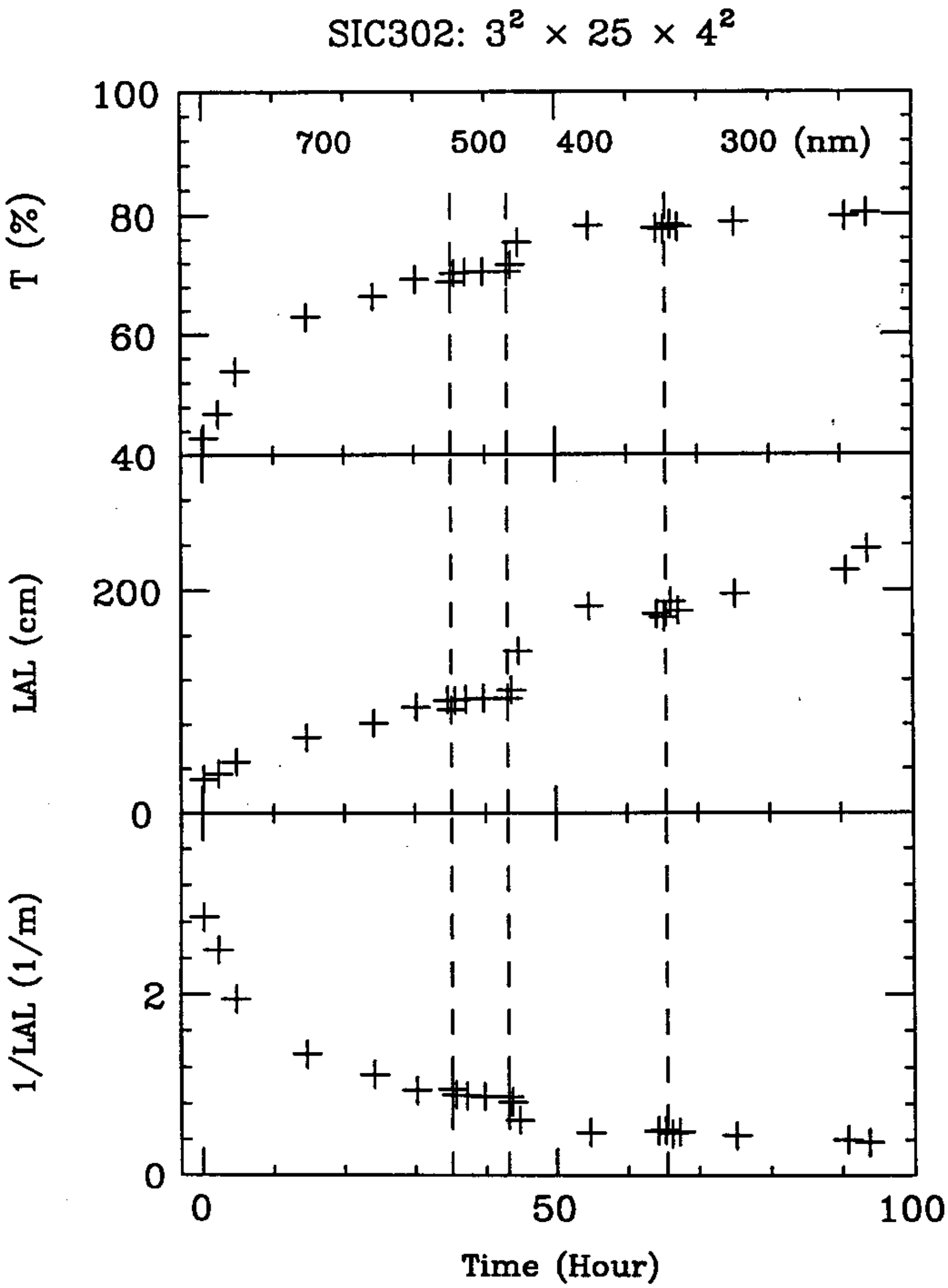

Figure 2: Transmittance (a), light attenuation length (b) and color center density (c) of SIC302 are plotted as a function of time under optical bleaching by light of different wavelengths.

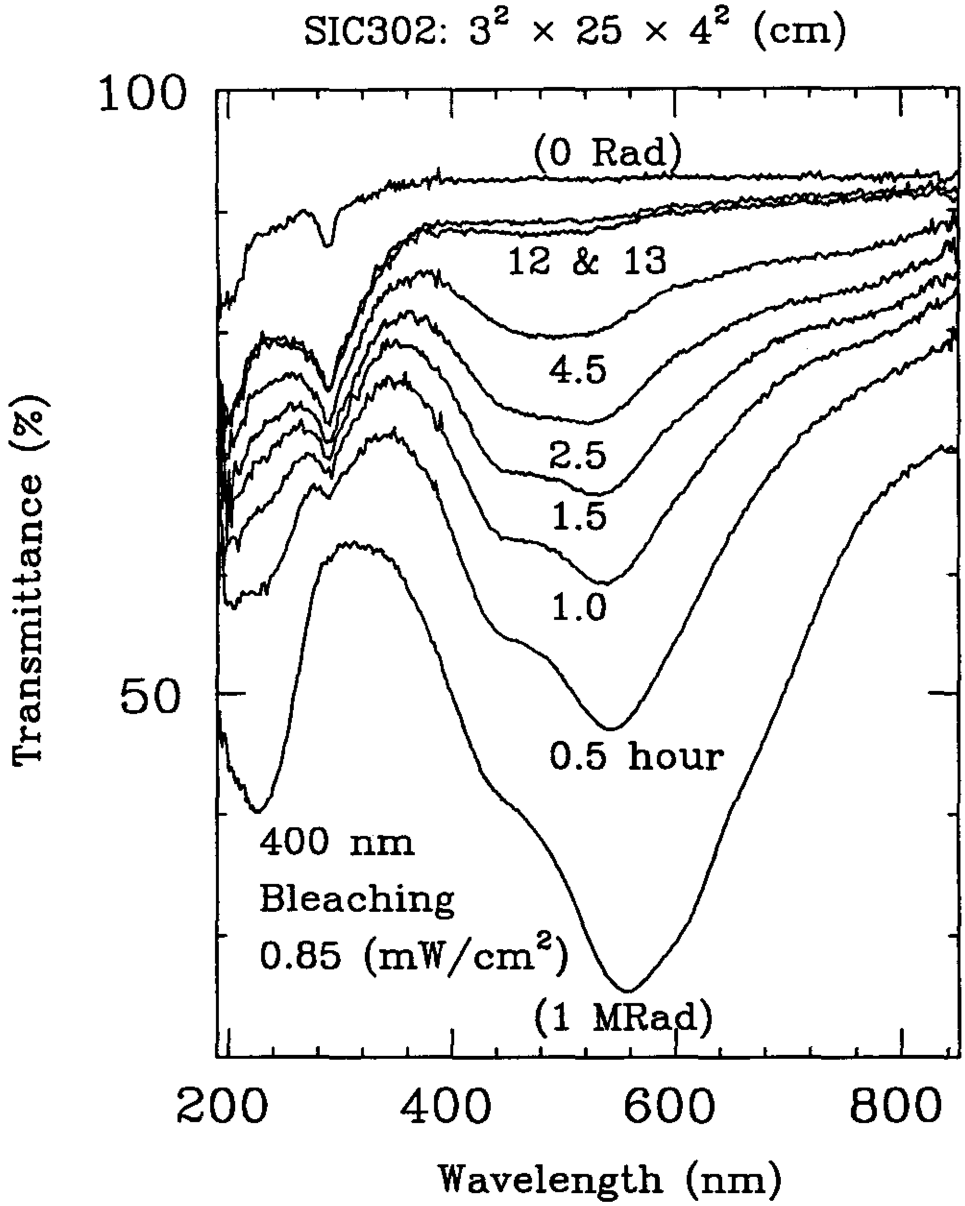

Figure 3: Transmittance of SIC302 are plotted as a function of wavelength under optical bleaching by 400 nm light.

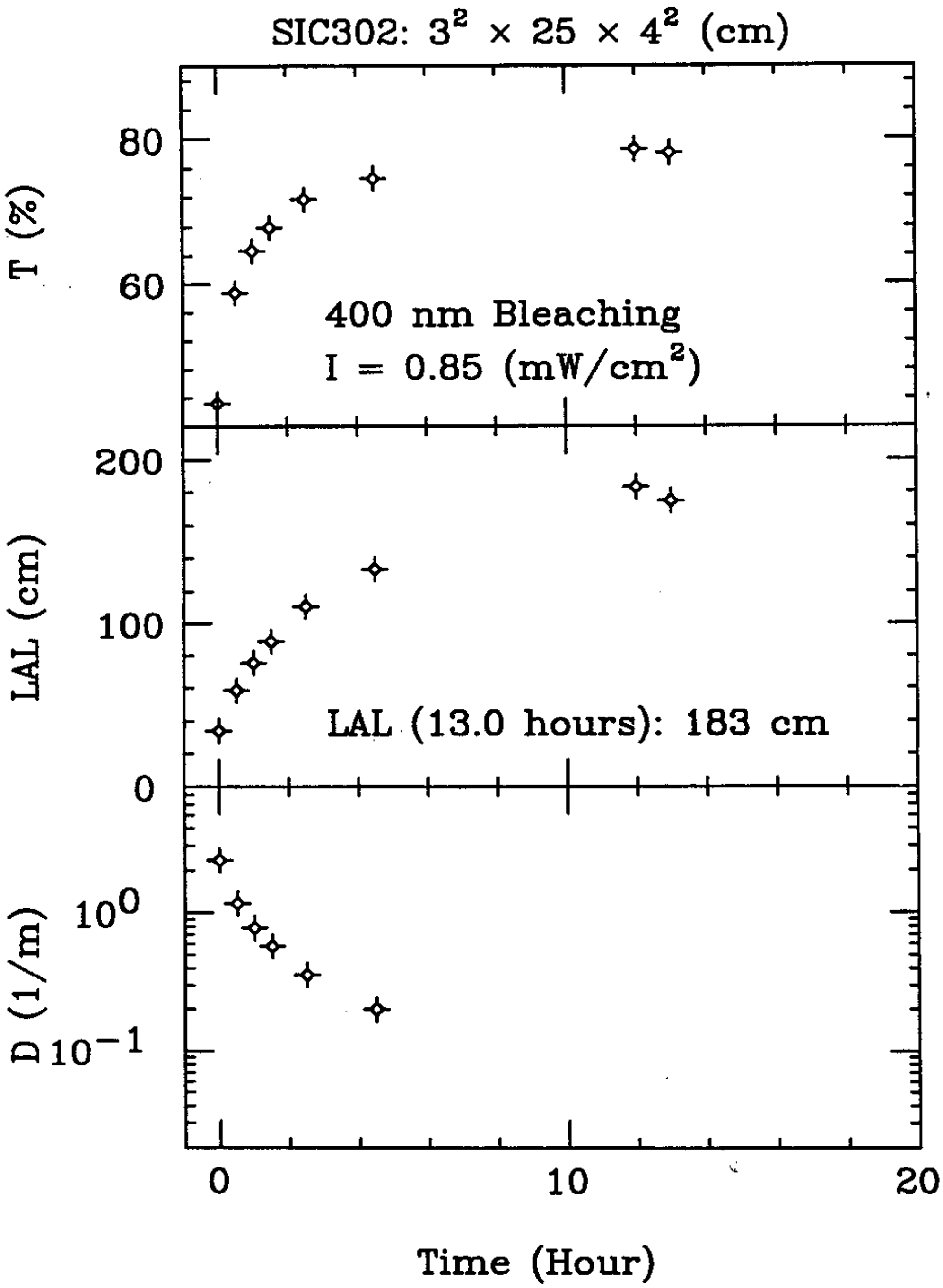

Figure 4: Transmittance (a), light attenuation length (b) and bleacgable color center density (c) of SIC302 are plotted as a function of time under optical annealing with 400 nm light.

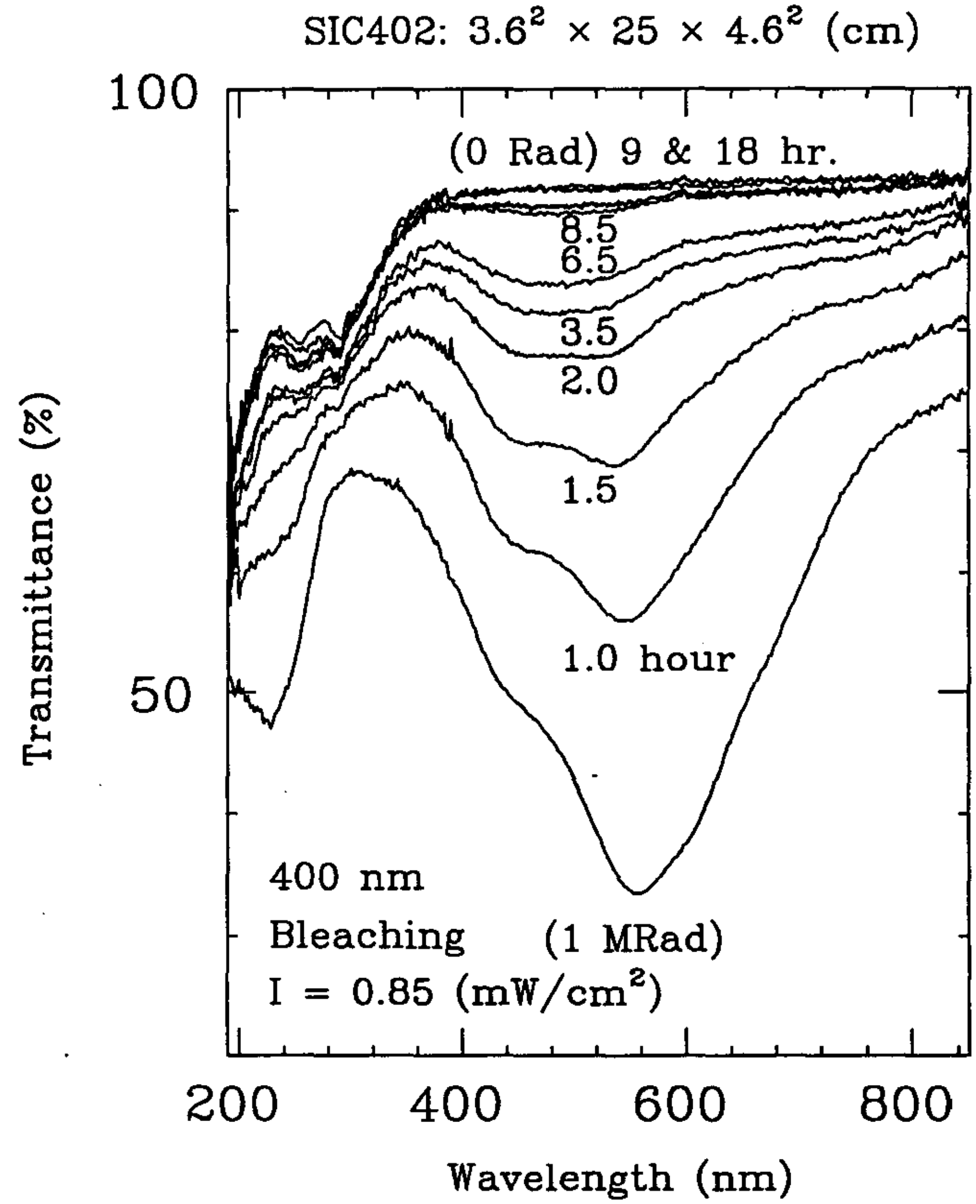

Figure 5: Transmittance of SIC402 are plotted as a function of wavelength under optical bleaching by 400 nm light.

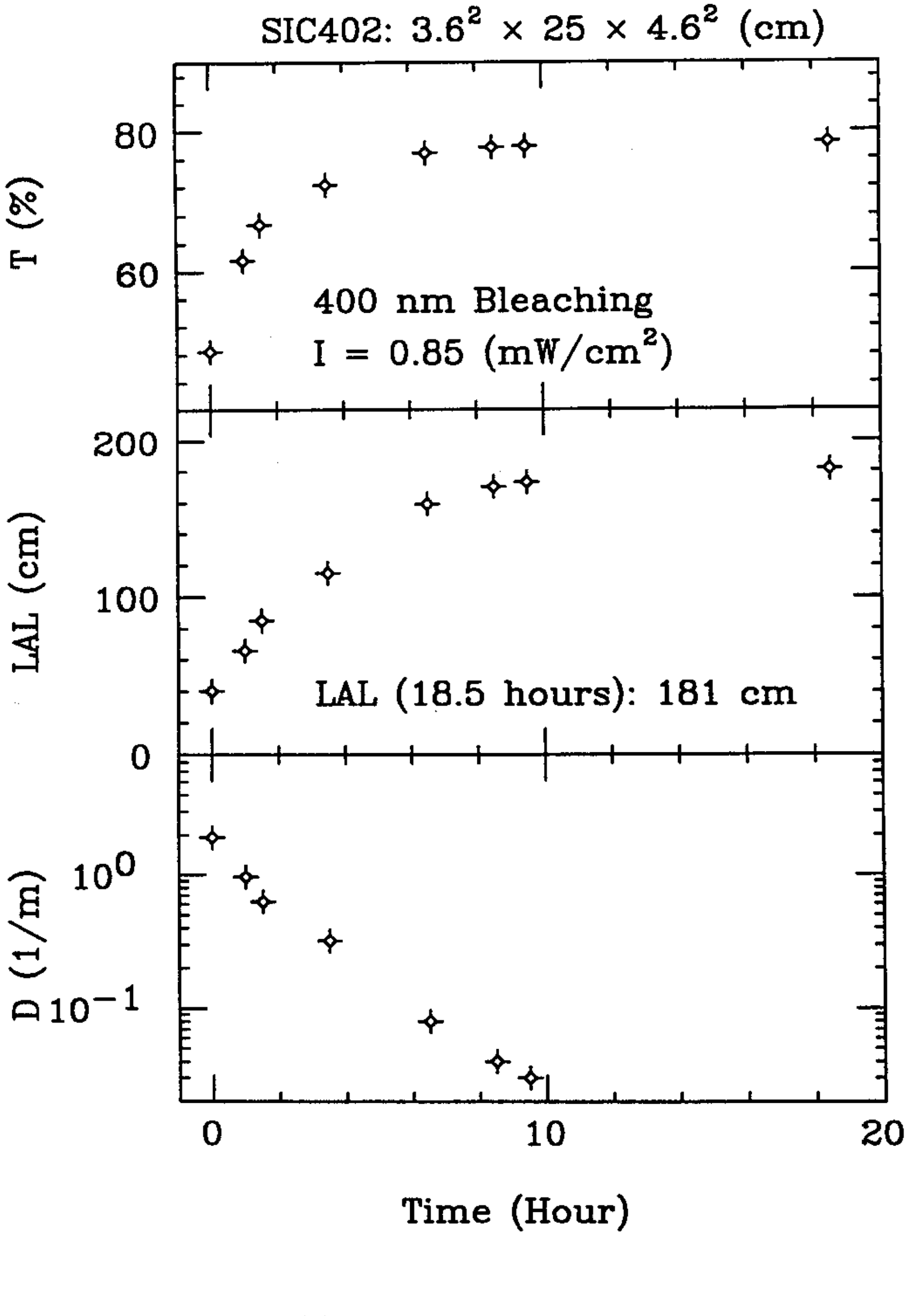

Figure 6: Transmittance (a), light attenuation length (b) and bleachable color center density (c) of SIC402 are plotted as a function of time under optical annealing with 400 nm light.