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Proper Interpretation of Photoconductive Decay Transients in Semiconductors Having Finite Surface Recombination Velocity

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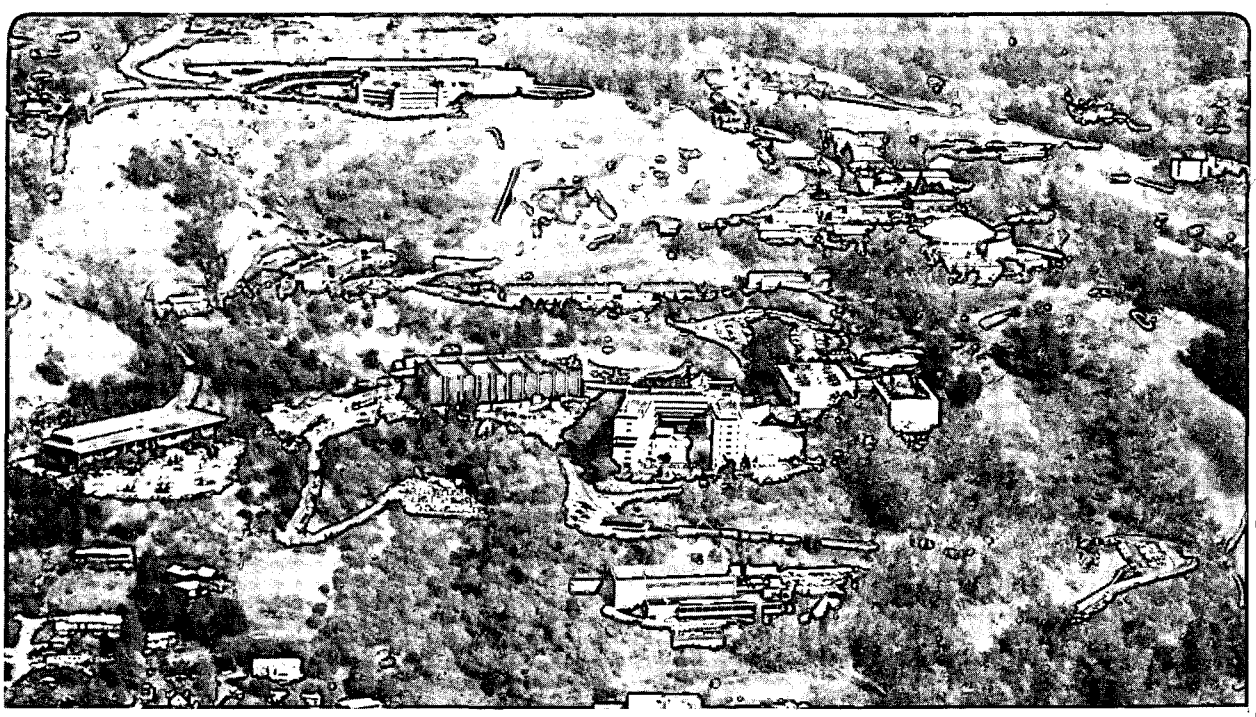

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Proper Interpretation of Photoconductive Decay Transients in Semiconductors Having Finite Surface Recombination Velocity

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Abstract

The influence of finite surface recombination velocity on the proper interpretation of photoconductive decay (PCD) transients in semiconductors is discussed. The limitations of simple analytical equations which relate the observed effective lifetime to the material parameters are considered. It is shown that, under most circumstances, the correct application of the appropriate analytical expression requires some prior knowledge of the material parameters under investigation. Several methods are proposed to extract useful information from PCD experiments. Finally, the practicality of these methods is investigated by measuring the effective lifetimes of high purity germanium and float-zone silicon using a noncontact PCD technique.

Introduction

The bulk minority carrier lifetime (τ_B) and surface recombination velocity (S) often play critical roles in determining semiconductor device performance. The performance of semiconductor solar cells and radiation detectors (far-infrared to γ-ray), in particular, relies on the optimization of these parameters. The physical and chemical processes that are involved in the fabrication of such devices often affect these parameters and hence influence the electrical properties of the devices. For instance, accidental introduction of trace metallic impurities, such as Fe, Cu, or Ni, into silicon during thermal processing can seriously degrade Si radiation detector resolution by reducing the bulk lifetime. Monitoring τ_B and S between key device processing steps in a fabrication environment would therefore provide valuable insight for process development and optimization. Several noncontact techniques have been developed in recent years to furnish such a capability.[1-6] Contactless photoconductive decay techniques eliminate the need for contact fabrication and are ideal characterization tools in a fabrication environment. Common to all of these techniques is the extraction of an effective lifetime from the measured PCD transients. A vast collection of literature exists concerning the determination of material parameters from the observed effective lifetimes of PCD measurements.[7-10] However, each of these data analysis schemes has critical limitations and their improper usage can result in orders of magnitude errors in the extracted quantities. In this paper, we discuss some of the limitations involved in the interpretation of PCD transients using the exact solutions to the equations governing the decay of the photoexcited carriers in a semiconductor. Finally, we apply our theoretical results to analyze the PCD transients of high resistivity Si and Ge measured by a contactless PCD technique.

Theoretical Results

Recombination of the photogenerated carriers on the surface of a semiconductor influences PCD transients extensively and introduces complications in the data analysis. In the ideal case, where

surface effects are ignored and $S = 0$, the PCD transients are characterized by the bulk lifetime, and the photo-enhanced conductivity, σ, decays according to the simple function $\exp(-t/\tau_B)$. That is, the PCD transients are governed by a single lifetime and the data analysis is straight forward. In real situations, however, finite surface recombination rates result in multiexponential transients and the extraction of a unique decay lifetime becomes more difficult. However, multiexponential PCD transients often contain a dominant "effective lifetime", τ_{eff}.[7] In its simplest form, the dependence of τ_{eff} on τ_B and S is as follows:

$$\frac{1}{\tau_{eff}} = \frac{1}{\tau_B} + \frac{2S}{L} \tag{1}$$

where L is the thickness of the sample.[8] Using this simple equation, the experimental determination of τ_B and S is normally accomplished by repeating the measurement for samples of varying thickness. The straight line which results from plotting $1/\tau_{eff}$ vs. $1/L$ has a slope equal to $2S$ and intersects the y-axis at $1/\tau_B$. In the following, we will examine the limitations of Eq. 1 and we will determine other approximate expressions for the effective lifetime by analyzing different limiting cases of the exact solutions to the photoconductive decay problem.

The decay of photoexcited carriers in a semiconductor after the termination of the excitation pulse is governed by the solutions to the partial differential equation:

$$\frac{\partial n(x,t)}{\partial t} = D\frac{\partial^2 n(x,t)}{\partial x^2} - \frac{n(x,t)}{\tau_B} \tag{2}$$

where $n(x,t)$ is the photoexcited carrier concentration and D is the minority carrier diffusion coefficient.[7-10] The corresponding boundary conditions are:

$$D\left.\frac{\partial n(x,t)}{\partial x}\right|_{x=o} = Sn(0,t), \tag{3}$$

$$D\frac{\partial n(x,t)}{\partial x}\bigg|_{x=L} = Sn(L,t) \tag{4}$$

and the initial condition depends on the excitation optical pulse shape (width and height), wavelength, and intensity. Luke and Cheng have analyzed this problem for a variety of optical pulses.[9]

The solution to Eq. 2 is of the form

$$n(x,t) = \sum_{j=0}^{\infty}\left[A_j \cos\left(\alpha_j x\right) e^{-t/\tau_{1,j}} + B_j \sin\left(B_j x\right) e^{-t/\tau_{2,j}}\right] \tag{5}$$

where $\tau_{1,j}$ and $\tau_{2,j}$ are given by

$$\frac{1}{\tau_{1,j}} = \frac{1}{\tau_B} + \alpha_j^2 D, \text{ and } \frac{1}{\tau_{2,j}} = \frac{1}{\tau_B} + \beta_j^2 D.$$

The constants A_j, B_j, α_j, and β_j are determined from the initial and boundary conditions.[9] As pointed out by Luke and Cheng, the odd terms in Eq. 5 die out rapidly with time and the decay is governed primarily by the even terms;

$$n(x,t) = \sum_{j=0}^{\infty} n_j(x) e^{-t/\tau_{eff,j}} \tag{6}$$

where $\tau_{eff,j}$ is defined as the "effective lifetime" of the jth solution and $n_j(x) \propto \cos(\alpha_j x)$. It can immediately be seen that the decay of the photoexcited carriers is governed by a multiexponential function with the characteristic decay constants given by:

$$\frac{1}{\tau_{eff,j}} = \frac{1}{\tau_B} + \alpha_j^2 D. \tag{7}$$

The constants α_js are determined by the boundary conditions 3 and 4, and they are the solutions to the transcendental equation:

$$\cot\left(\frac{\alpha_j L}{2}\right) = \frac{2D}{SL}\left(\frac{\alpha_j L}{2}\right). \tag{8}$$

Equation 7 then is the generalization of the simple Eq. 1.

In the following, solutions to Eqs. 2–4 are presented for a wafer thickness L, minority carrier bulk lifetime τ_B, and surface recombination velocity S. The values of the parameters used in the model are varied and their effects on the PCD transients are presented. The diffusion coefficient, D, is kept constant throughout the simulations since we are concerned with the effect of the variations of τ_B and S on the PCD transients. Furthermore, D is not affected by process related contamination at room temperature which is of interest to us in our PCD experiments. Several elementary assumptions are used to derive simple analytical expressions which relate the experimentally observed effective lifetime, τ_{eff}, to L, τ_B, D, and S. Comparisons are made between the exact solutions and the analytical expressions.

Figure 1 shows the calculated decay of the photoexcited minority carrier concentration for a typical high resistivity p-type Si ($\tau_B = 10^{-3}$ sec, $D = 32$ cm^2/sec) at room temperature. This figure reveals the inherent difficulties that may be encountered in a PCD experiment. Curve I in Fig. 1 is the result of the simulation for a sample with a thickness of 500 μm and a surface recombination velocity of 100 cm/sec. It is clear that the decay is governed by a single exponential with an "effective lifetime", τ_{eff}, which is equal to the first decay constant of the series solution of Eq. 6, τ_o. As the parameters L and S of the simulation are varied, the transients change their simple shape and behave according to a complex multiexponential function. Curve II in Fig. 1 ($S = 30{,}000$ cm/sec, $L = 500$ μm), shows a multiexponential decay which is dominated by a single decay con-

stant that can be estimated by considering the asymptotic limit of the transient. Finally, the transient represented by curve III (S = 50,000 cm/sec, L = 1000 μm) does not contain a unique controlling decay constant in the time scale shown. In order to extract an appropriate "effective lifetime" from this type of a multiexponential transient, one must record the change in the photoconductivity with a sensitivity of one part per thousand or better (i.e., $\Delta\sigma/\sigma_o < 0.005$). However, in typical PCD transient measurements, reasonable signal to noise ratios are achieved when the sensitivity is on the order of one part per hundred ($\Delta\sigma/\sigma_o > 0.01$). Consequently, in practical situations, only a limited range in values of the material parameters result in a dominant effective lifetime in the PCD transients. When a clear "effective lifetime" *is* present in the PCD transients, numerical modeling shows that it will be equal to the characteristic decay constant of the first term in the series solution of Eq. 6, namely τ_o. Higher terms in the series solution are characterized by much shorter decay times.[9]

In typical photoconductive decay experiments, τ_{eff} and L are measured while attempting to determine τ_B and S. In certain situations, analytical expressions can be derived which relate τ_{eff}, L, τ_B, and S. In particular, there are three distinct limits in which simple analytical expressions describe the relationship between these parameters. In the limit where $S << 2\,D/L$, Eq. 8 is approximated by:

$$\cot\left(\frac{\alpha_o L}{2}\right) \approx \frac{2}{\alpha_o L} = \frac{D\alpha_o}{S}$$

and thus Eq. 7 reduces to

$$\frac{1}{\tau_o} = \frac{1}{\tau_B} + \frac{2S}{L}. \qquad (9)$$

This equation is identical to Eq. 1, as the measured effective lifetime, τ_{eff}, and τ_o are identical.

A second expression can be approximated in the limit where $S > \pi D/L$. In this limit, Eq. 8 can be rewritten in a form which can be expanded:

$$\frac{\alpha_o L}{2} = \cot^{-1}\left(\frac{D\alpha_o}{S}\right) \approx \frac{\pi}{2} - \frac{D\alpha_o}{S}.$$

This approximation leads to the following analytical expression for the effective lifetime:

$$\frac{1}{\tau_o} = \frac{1}{\tau_B} + \frac{\pi^2 S^2}{\left(SL + 2D\right)^2} D. \tag{10}$$

In the extreme case of samples with large surface recombination velocities ($S >> 2\,D/L$), where the surfaces act as "infinite sinks" for the photoexcited carriers and the lifetime determining factor is the rate of diffusion of the carriers to the surface, then Eq. 10 can be approximated by

$$\frac{1}{\tau_o} = \frac{1}{\tau_B} + \frac{\pi^2}{L^2} D. \tag{11}$$

To illustrate the extent of the applicability of the analytical expressions described above, we have compared the results of computer modeling to Eqs. 9–11. Figure 2 shows the dependence of the effective lifetime on sample thickness. The calculated results using the exact solution to Eq. 2 are compared with the approximations of Eqs. 9 and 10. The bulk lifetime and the diffusion coefficient were kept constant throughout these calculations ($\tau_B = 10^{-3}$ sec, $D = 32$ cm^2/sec). Figure 2 displays the dependence of τ_{eff} on L for various values of S. In the case of a relatively low surface recombination velocity ($S = 80$ cm/sec), the exact solution can be approximated by the simple Eq. 9 over a wide range of sample thicknesses (100 μm < L < 1 cm) (Fig. 2a). In the range 100 μm < L < 1 cm and for moderate values of S, neither one of the analytical expressions derived above can exclusively approximate the dependence of τ_{eff} on L (Fig. 2b). When the surface recombination

velocity increases to $S = 10^4$ cm/sec, however, the effective lifetime dependence on sample thickness is approximated well by Eq. 10 (Fig. 2c).

The relationship between τ_{eff} and S follows a similar behavior to that of τ_{eff} and L. Figure 3 shows the results of the calculations of τ_{eff} as a function of surface recombination velocity for samples of varying thickness. For L = 10,000 μm (Fig. 3a), Eq. 10 approximates the exact solution for a wide range of surface recombination velocities (1 cm/sec < $S < 10^5$ cm/sec). For L = 2000 μm (Fig. 3b), Eq. 9 can be used to approximate the relationship between τ_{eff} and S only for S < 200 cm/sec while Eq. 10 becomes a more accurate description of the exact solutions for S > 800 cm/sec. As the sample thickness is decreased to 200 μm, the range of applicability of Eq. 9 extends to encompass surface recombination velocities between zero and 2000 cm/sec (Fig. 3c). The limit of Eq. 11 can also be observed in Figs. 3b and 3c for $S > 10^4$ cm/sec, at which point the surface acts as an infinite sink for the photoexcited carriers and the effective lifetime becomes insensitive to further variations of S.

The examples above clearly show that simple analytical expressions, such as Eqs. 9, 10 or 11, can only be used to accurately determine the bulk lifetime and the surface recombination velocity for a limited range of material parameters in PCD measurements. This restriction introduces a significant limitation in the accurate determination of τ_B and S: the experimenter must have some prior knowledge of the variables under investigation in order to apply the correct equation. For example, ordinarily, the effective lifetimes of the samples of varying thickness but identical surface conditions are measured and $1/\tau_{eff}$ vs. $1/L$ is plotted.[1,11] According to Eqs. 1 and 9, the slope of the resulting line will be equal to $2S$ and the y intercept will be $1/\tau_B$. The application of these equations, however, is justified only for a limited set of material parameters as was demonstrated above, and their inappropriate utilization will lead to an incorrect estimation of S and τ_B. This is shown in Fig. 4 where $1/\tau_{eff}$ vs. $1/L$ has been plotted using the calculated results from the exact solution of Eq. 2 ($D = 32$ cm^2/sec, $\tau_B = 10^{-3}$ sec). Curve I in Fig. 4, which shows the results of the calculation for S

= 80 cm/s, reveals a linear dependence of $1/\tau_{eff}$ on $1/L$. The exact solutions can accurately be described by the simple analytical expression of Eq. 9. The slope of this line is indeed equal to $2S$ and the y intercept furnishes the bulk lifetime. Curve II, on the other hand, represents the results of a similar calculation for $S = 10^4$ cm/s. It is apparent that the relationship between $1/\tau_{eff}$ and $1/L$ is nonlinear in this case. The application of Eq. 9 to the linear part of this curve (dashed line) would yield the wrong estimate for τ_B, in fact, it would result in a negative τ_B. The slope of the linear part of the curve, however, still provides a good approximation of the surface recombination velocity and the y-intercept of the nonlinear curve also furnishes the bulk lifetime.

The discussion above demonstrates that the photoconductive decay transients of real samples exhibit a complex dependence on key material parameters such as the bulk lifetime, diffusion coefficient, and surface recombination velocity. In spite of the existence of several simple analytical expressions which relate the observed effective lifetime to the material parameters such as τ_B, S, and L, the application of these formulae in the interpretation of experimental photoconductive decay transients should be carried out with discretion. The exact solution of the equation governing the photoconductive decay may be necessary to accurately simulate the dynamics of nonequilibrium carriers in a PCD experiment.

Experimental Results and Discussion

We performed noncontact effective lifetime measurements on high resistivity floating zone silicon (p-type, N_A-$N_D \sim 10^{11}$ cm^{-3}) and high purity germanium (p-type, N_A-$N_D \sim 10^{10}$ cm^{-3}). Our measurement system is based on the principle of inductively coupled photoconductive decay measurement.[1,12] A high power infrared LED (power = 1.5 W, λ = 875 nm, $\Delta\lambda$ = 100 nm, square pulse, pulsewidth = 150 μs and pulse fall time < 250 ns) was used as the excitation source for the silicon samples. A strobe light (power = 40 W, broadband, Gaussian pulse, FWHM ≈ 15 μs) provided the excitation source for the germanium samples. We used filters to keep the optical excitation

intensities low enough to insure that small signal conditions were satisfied. The minority carrier lifetime becomes a function of the photoexcited carrier concentration at large excitation intensities introducing further complications in the analysis of the PCD transients. The measurements were performed on silicon samples of varying thickness (0.025 cm < L < 0.183 cm) which were etched with the standard HNO_3:HF (3:1) for approximately 1 minute followed by an isopropanol quench. Next, the samples were etched by H_2O:HF (5:1) for 2 minutes followed by a H_2O rinse for one minute and were blown dry by nitrogen gas.

The silicon samples were stored at room temperature under atmospheric conditions for approximately 24 hours before the PCD measurements were performed. It is well known that a native oxide layer (approximately 10–30 Å) grows on the freshly etched silicon surface under such conditions over a 24 hour period.[13,14] The formation of the native SiO_2 on the silicon surface creates disordered interfacial structures which contain defects that act as recombination centers.[15] We have observed direct evidence of the growth of the native SiO_2 on the silicon surface, after a standard HF treatment, manifested by the deterioration of the effective lifetime over a 24 hour period. These results, which will be presented in a future report, show good agreement with ellipsometry measurements performed by other investigators.[16,17] In this paper, we present only the results obtained using silicon samples with a thin native SiO_2 layer.

A typical photoconductive decay transient for a Si sample is shown in Fig. 5a. The effective lifetime was obtained by curve fitting the asymptotic part of the decay signal for each thickness with an exponential function (Fig. 5b). Figure 6 is a plot of $1/\tau_{eff}$ on $1/L$ and illustrates its nonlinear characteristics. The experimental data have been curve fitted using the exact solution to Eq. 2 with the parameters: D = 30 cm^2/sec, S = 20,000 cm/sec and τ_B = 2500 μs (which is approximately equal to the vendor specified bulk lifetime of 3000 μs). Clearly, the application of a simple analytical expression such as Eq. 9 to the data is practically impossible in this case because of the extreme nonlinearity of the data.

Figure 7 shows the corresponding measurements on germanium samples. The Ge samples were etched following the same procedure used for the silicon. Again, the nonlinear dependence of $1/\tau_{eff}$ on $1/L$ is apparent. The fitting parameters for the Ge sample were $D = 85$ cm^2/sec, $S = 1300$ cm/sec and $\tau_B = 5000$ µs. It should be emphasized that due to the number of fitting parameters involved in the modeling of the experimental data, the uncertainties in the above values could be rather large. The numbers quoted here are for the best fit that we achieved.

To eliminate the number of fitting parameters in the analysis of PCD transients, several options can be exercised. First, by reducing the surface recombination velocity to a minimum, Eq. 9 can effectively be applied to determine τ_B. For high purity float-zone silicon samples ($\tau_B > 200$ µs), with thicknesses in the 250 µm–1500 µm range, this means that S has to be less than 1000 cm/sec. Such low values of surface recombination velocity in Si have been achieved by measuring the photoconductivity decay transients while the samples were immersed in a diluted HF solution.[1] The bulk lifetime can then be extracted by applying Eq. 9 to the data with no fitting parameters. Another solution is to determine the bulk lifetime of the samples using other techniques such as the open-circuit-voltage-decay measurement which rely on the switching of pn junctions.[18] However, this technique requires extensive sample processing and may not be particularly suitable to a fabrication environment. In any case, once the bulk lifetime has been determined, then the noncontact PCD measurement can be employed to determine the effects of various surface treatments on the effective lifetime of the sample. Since such treatments do not affect the bulk lifetime, the variations of τ_{eff} will be due solely to the modifications of the surface recombination velocity, provided that the sample thickness remains constant. To illustrate this point, we measured the effective lifetime of a Ge sample ($L = 0.4$ cm) before and after the deposition of a thin layer of amorphous germanium on the surface. The sample was etched first with the standard HNO_3:HF (3:1) for approximately one minute followed by an isopropanol quench, and then was blown dry by nitrogen gas. The effective lifetime of the sample was measured using the noncontact PCD technique described above and was equal to $(3 \pm 0.3) \times 10^{-3}$ sec. Subsequently, 600 Å of amorphous Ge was sputtered

on both surfaces of the sample. After the deposition of the amorphous layer, τ_{eff} decreased to (2.3 $\pm$ 0.3) x 10^{-4} sec. The removal of the amorphous layer by etching the sample in HNO_3:HF (3:1) solution resulted in the increase of τ_{eff} back to its original value of (2.9 $\pm$ 0.3) x 10^{-3} sec. Since the deposition and the subsequent removal of the thin amorphous layer have no effect on the bulk properties of the sample, we conclude that the order of magnitude decrease in τ_{eff} occurred due to the alteration of the electronic properties of the surface, presumably as a result of the introduction of a large concentration of surface states that increased the surface recombination velocity.

Conclusion

The optimization of material parameters such as the bulk lifetime and the surface recombination velocity plays a key role in enhancing the performance of various semiconductor devices, in particular, semiconductor radiation detectors and photovoltaic devices. Contactless photoconductive decay experiments are ideally suited for investigating the effects of various fabrication processes on τ_B and S. However, complications occur in the data analysis of the PCD transients, because the effective lifetimes extracted from such measurements are complicated functions of the material parameters such as the bulk lifetime, the surface recombination velocity, the thickness and the diffusion coefficient. The accurate description of the photoconductive decay transients requires the exact solution to the equation governing the decay of the photoexcited carriers in a semiconductor. The elementary analytical expressions, which result from implementing simple assumptions to the exact solutions and relate the observed effective lifetime to the material parameters, have a limited range of applicability. We have shown that a prior knowledge of the material parameters may be required for the appropriate utilization of these analytical expressions in the interpretation of the experimental data. If the initial information regarding the relevant material parameters is insufficient, then only the comparison between measured effective lifetimes is justified. For example, the effects of a particular surface treatment on S can be determined by comparing the measured τ_{eff} of a sample before and after the process, provided that the values of the D, τ_B and L remain constant.

This procedure was demonstrated experimentally by measuring the effective lifetime of a Ge sample before and after the deposition of a thin layer of amorphous germanium. The effective lifetime was reduced by an order of magnitude due to the amorphous layer. We have explored the applicability of a noncontact PCD technique for process monitoring and have suggested bounds over which simple analytical expressions can be used to interpret PCD data. Despite of the inherent difficulties in the extraction of τ_B and S from τ_{eff}, the contactless PCD measurement has utility in process monitoring, allowing rapid comparison of τ_{eff} with an established norm for the process.

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Figure Captions

Figure 1: Calculated normalized photoexcited carrier concentration as a function of time. The values used in the modeling are $\tau_B = 10^{-3}$ sec, $D = 32$ cm^2/sec, and (I) $S = 100$ cm/sec, $L = 500$ μm (+++); (II) $S = 30{,}000$ cm/sec, $L = 500$ μm (•••); (III) $S = 100{,}000$ cm/sec, $L = 1000$ μm (ooo).

Figure 2: Comparison of the calculated dependence of τ_{eff} on L using the exact solution to Eq. 2 (•••) and the approximate analytical solutions given by Eq. 9 (---), and Eq. 10 (—). The values used are $\tau_B = 10^{-3}$ sec, $D = 32$ cm^2/sec; and (a) $S = 80$ cm/sec, (b) $S = 800$ cm/sec, (c) $S = 10{,}000$ cm/sec.

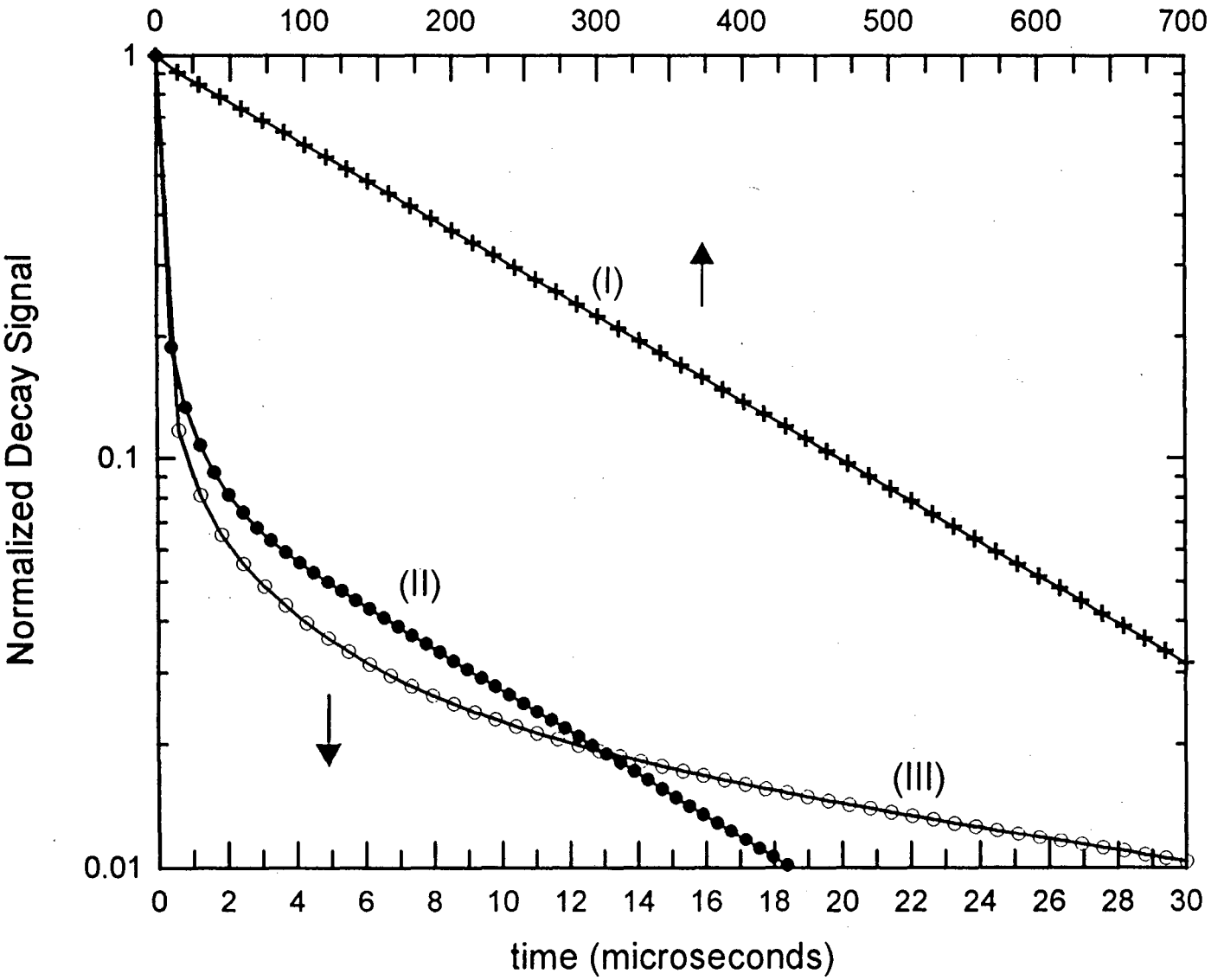
Figure 3: Comparison of the calculated dependence of τ_{eff} on S using the exact solution to Eq. 2 (•••) and the approximate analytical solutions given by Eq. 9 (---), and Eq. 10 (—). The values used are $\tau_B = 10^{-3}$ sec, $D = 32$ cm^2/sec; and (a) $L = 10000$ μm, (b) $L = 2000$ μm, (c) $L = 200$ μm.

Figure 4: Calculated results illustrating the effect of surface recombination velocity on the dependence of $1/\tau_{eff}$ vs. $1/L$ for (I) $\tau_B = 10^{-3}$ sec, $D = 32$ cm^2/sec, $S = 80$ cm/sec (+++); and (II) $\tau_B = 10^{-3}$ sec, $D = 32$ cm^2/sec, $S = 10{,}000$ cm/sec (•••).

Figure 5: (a) The normalized oscilloscope trace of a typical PCD transient. The sample is high resistivity floating zone silicon and the thickness is 0.17 cm. (b) The decay part of the transient plotted on a log-linear scale. There is a dominant decay mode with a characteristic effective lifetime of 110 μs.

Figure 6: $1/\tau_{eff}$ vs. $1/L$ for floating zone silicon samples. The nonlinearity of the experimental results (•••) is evident. The experimental data has been curve fitted using the exact solutions to Eq. 2. The parameters used in the model were: $D = 30$ cm^2/sec, $\tau_B = 2.5 \times 10^{-3}$ sec, $S = 20{,}000$ cm/sec. The nonlinear characteristics of the curve resembles the modeling results displayed in Fig. 4.

Figure 7: $1/\tau_{eff}$ vs. $1/L$ for germanium samples. The experimental data has been curve fitted using the exact solutions to Eq. 2. The parameters used in the model were: $D = 85$ cm^2/sec, $\tau_B = 5 \times 10^{-3}$ sec, $S = 1300$ cm/sec. The nonlinear characteristics of the experimental results are evident displayed in Fig. 4.



XBL 9312-1749

FIGURE 1

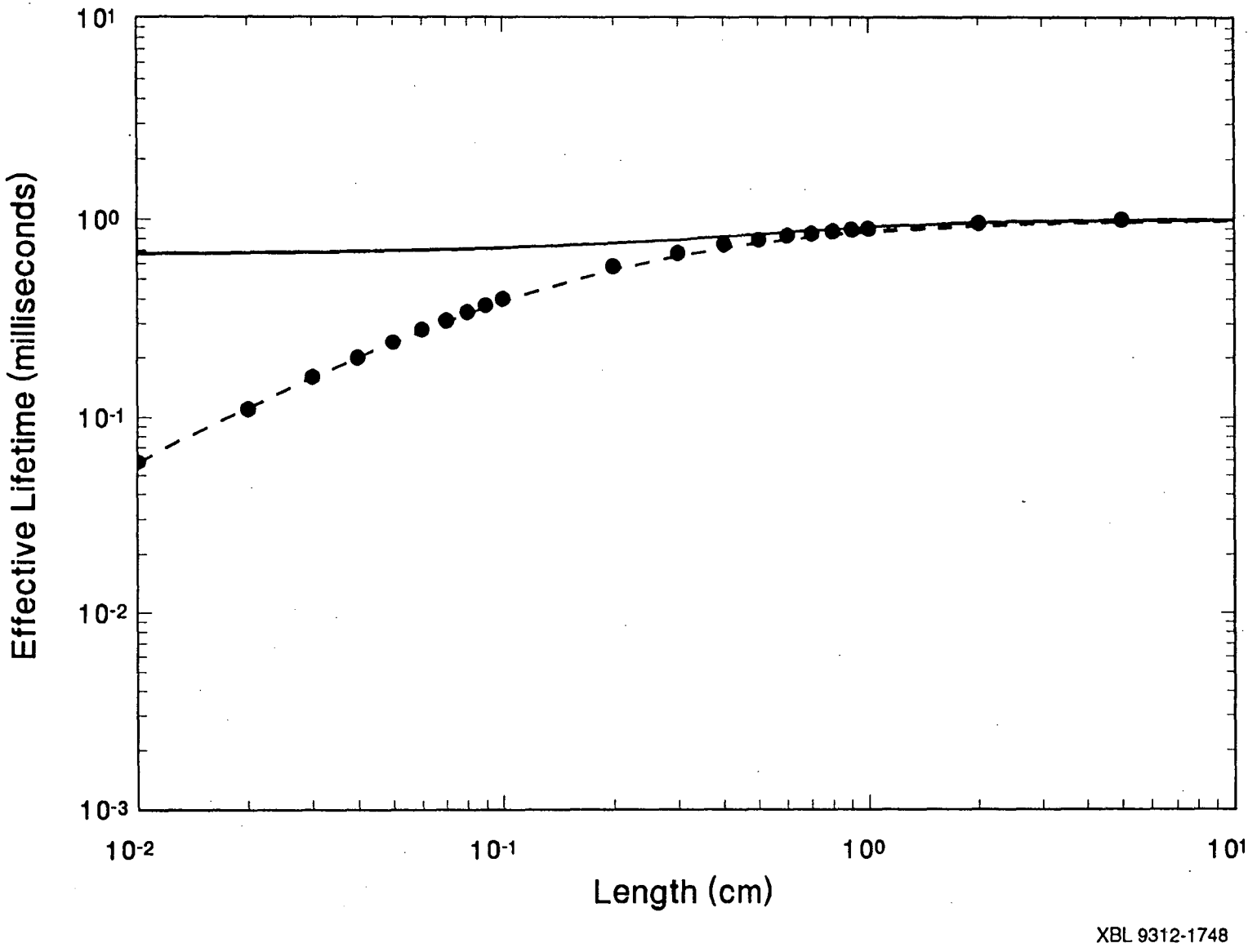

Effective Lifetime (milliseconds)
10¹
10⁰
10⁻¹
10⁻²
10⁻³
10⁻²
10⁻¹
10⁰
10¹
Length (cm)
XBL 9312-1748

FIGURE 2a

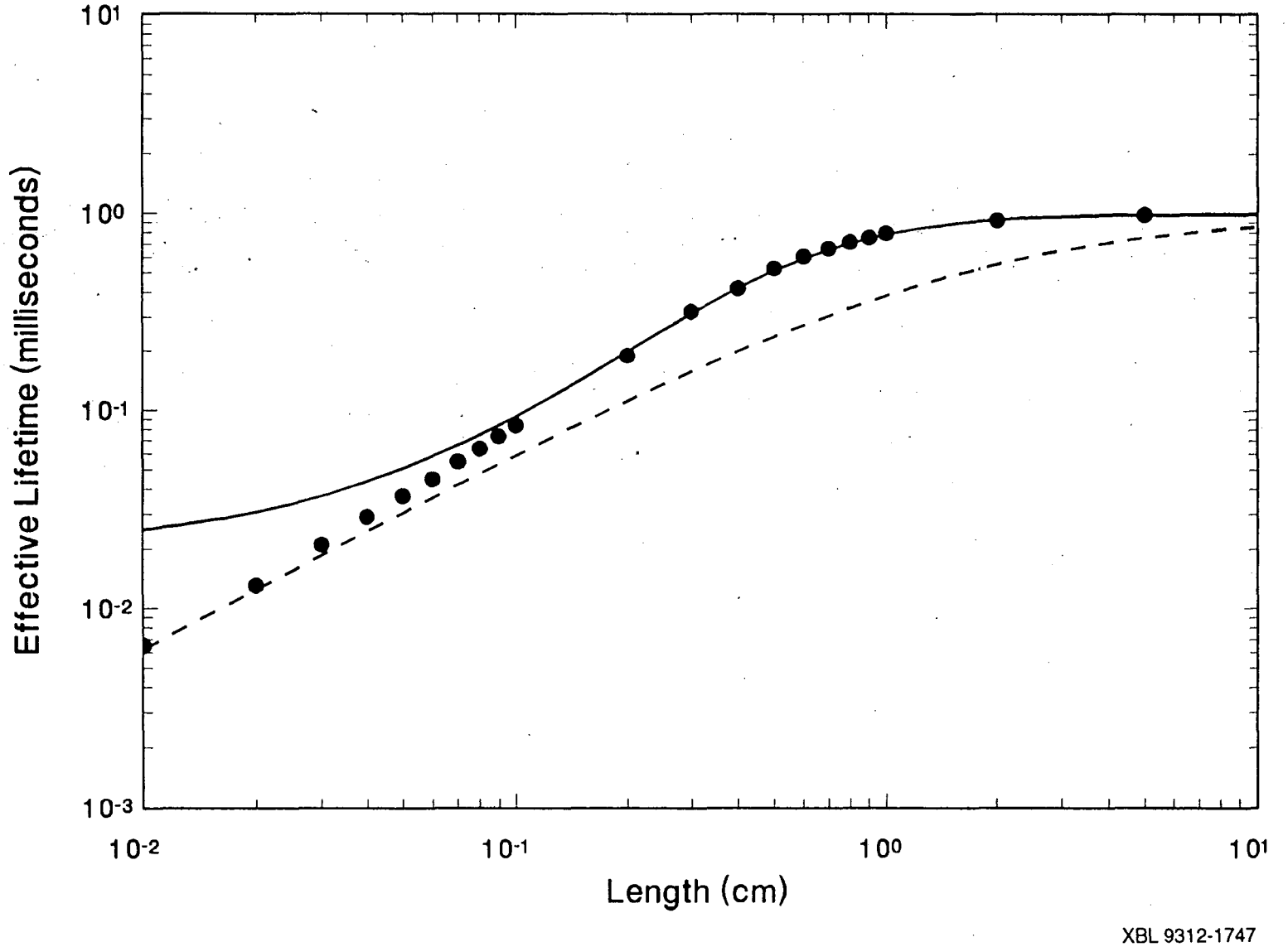

Effective Lifetime (milliseconds)
10¹
10⁰
10⁻¹
10⁻²
10⁻³
10⁻²
10⁻¹
10⁰
10¹
Length (cm)
XBL 9312-1747

FIGURE 2b

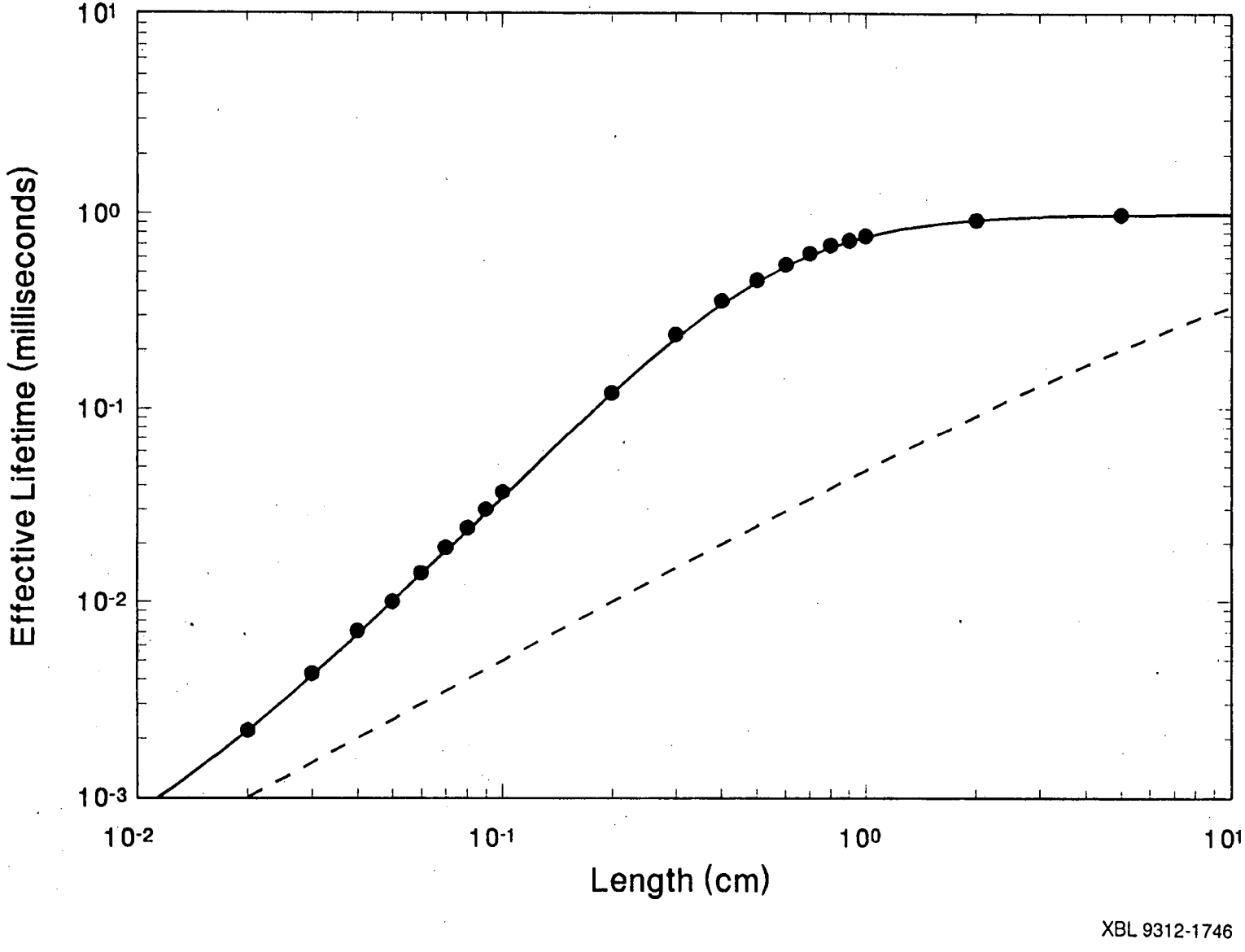

Effective Lifetime (milliseconds)
10¹
10⁰
10⁻¹
10⁻²
10⁻³
10⁻²
10⁻¹
10⁰
10¹
Length (cm)
XBL 9312-1746

FIGURE 2c

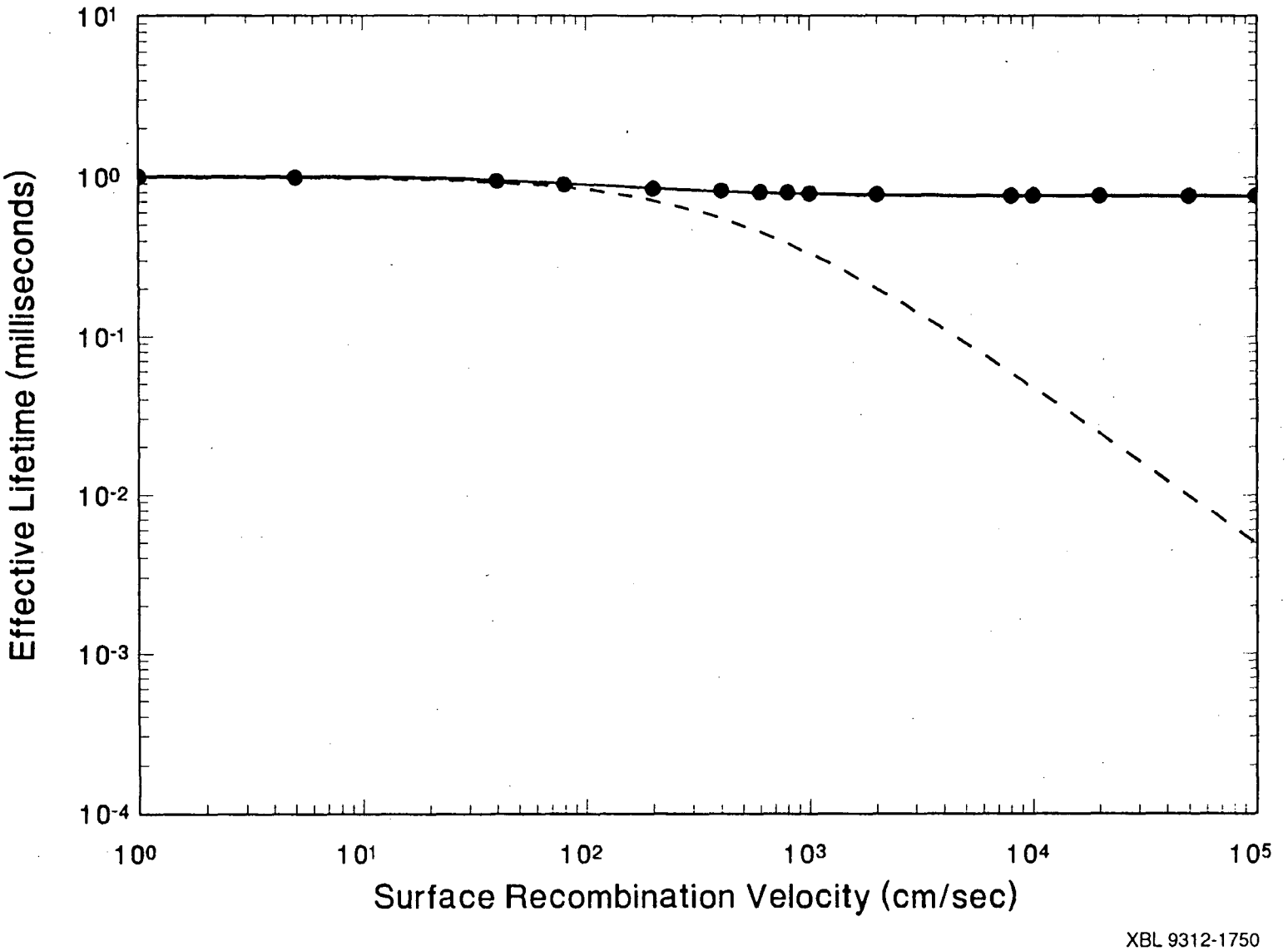

Effective Lifetime (milliseconds)
10¹
10⁰
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁰
10¹
10²
10³
10⁴
10⁵
Surface Recombination Velocity (cm/sec)
XBL 9312-1750

FIGURE 3a

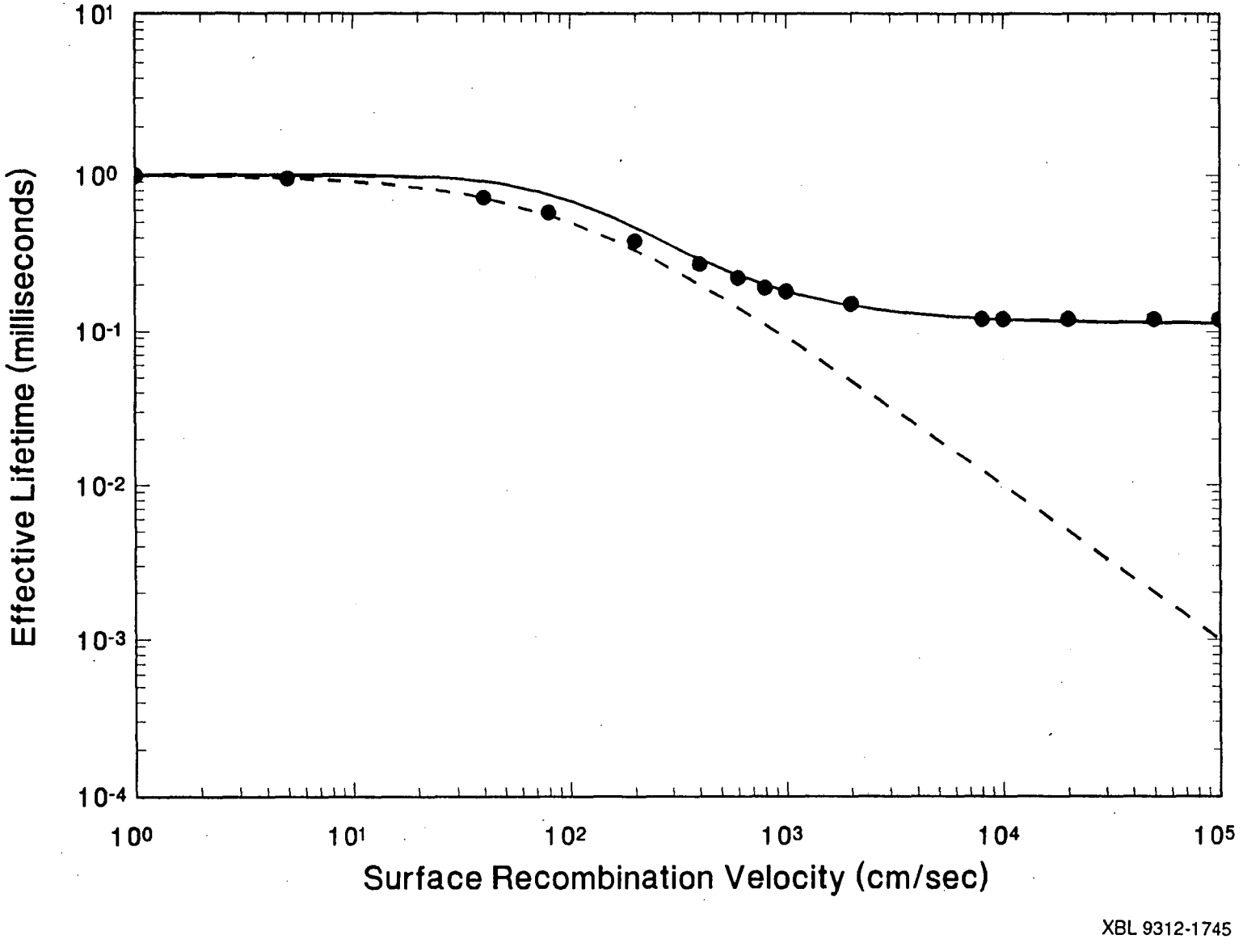

Effective Lifetime (milliseconds)
10¹
10⁰
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁰
10¹
10²
10³
10⁴
10⁵
Surface Recombination Velocity (cm/sec)
XBL 9312-1745

FIGURE 3b

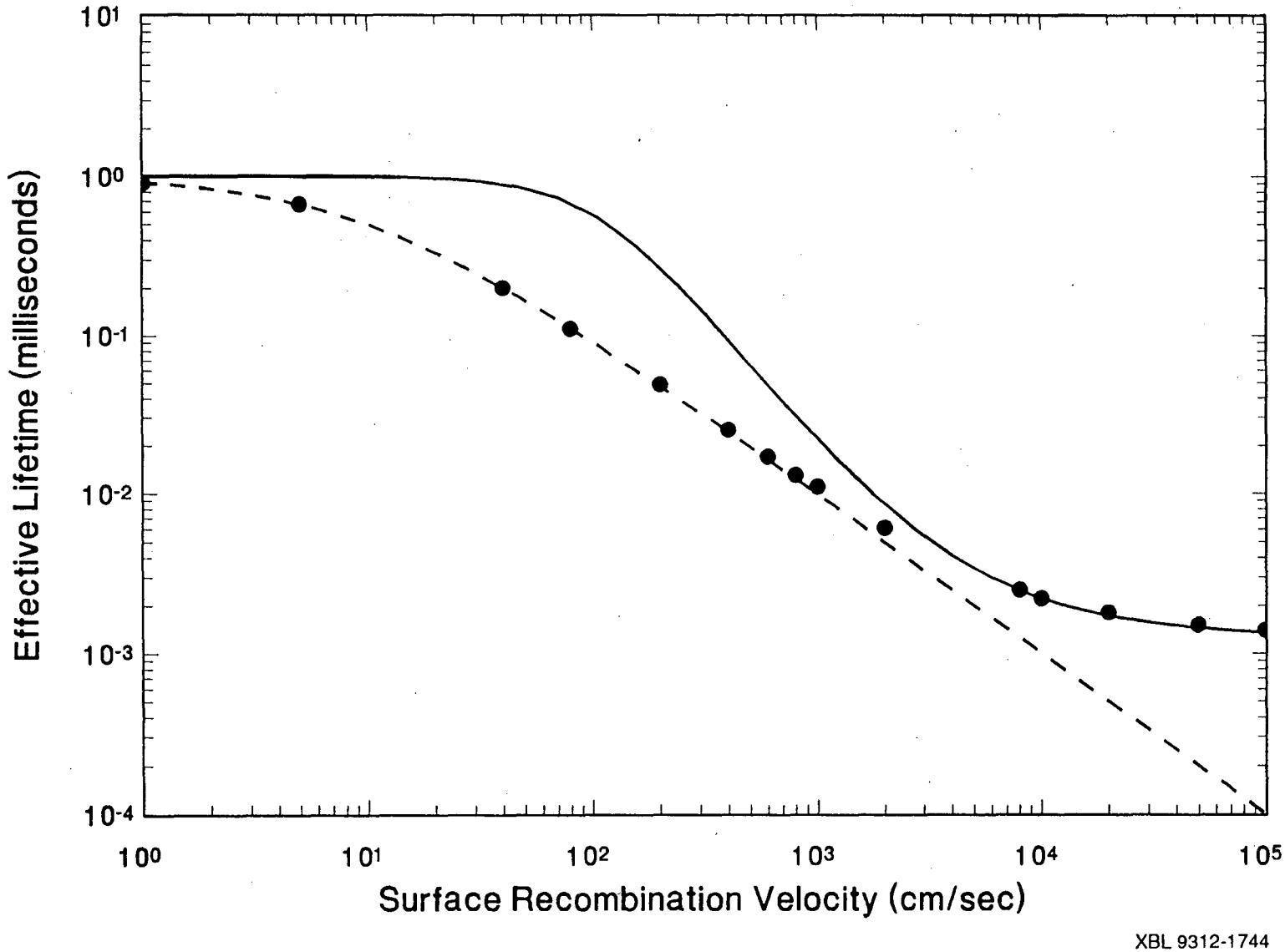

Effective Lifetime (milliseconds)
10¹
10⁰
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁰
10¹
10²
10³
10⁴
10⁵
Surface Recombination Velocity (cm/sec)
XBL 9312-1744

FIGURE 3c

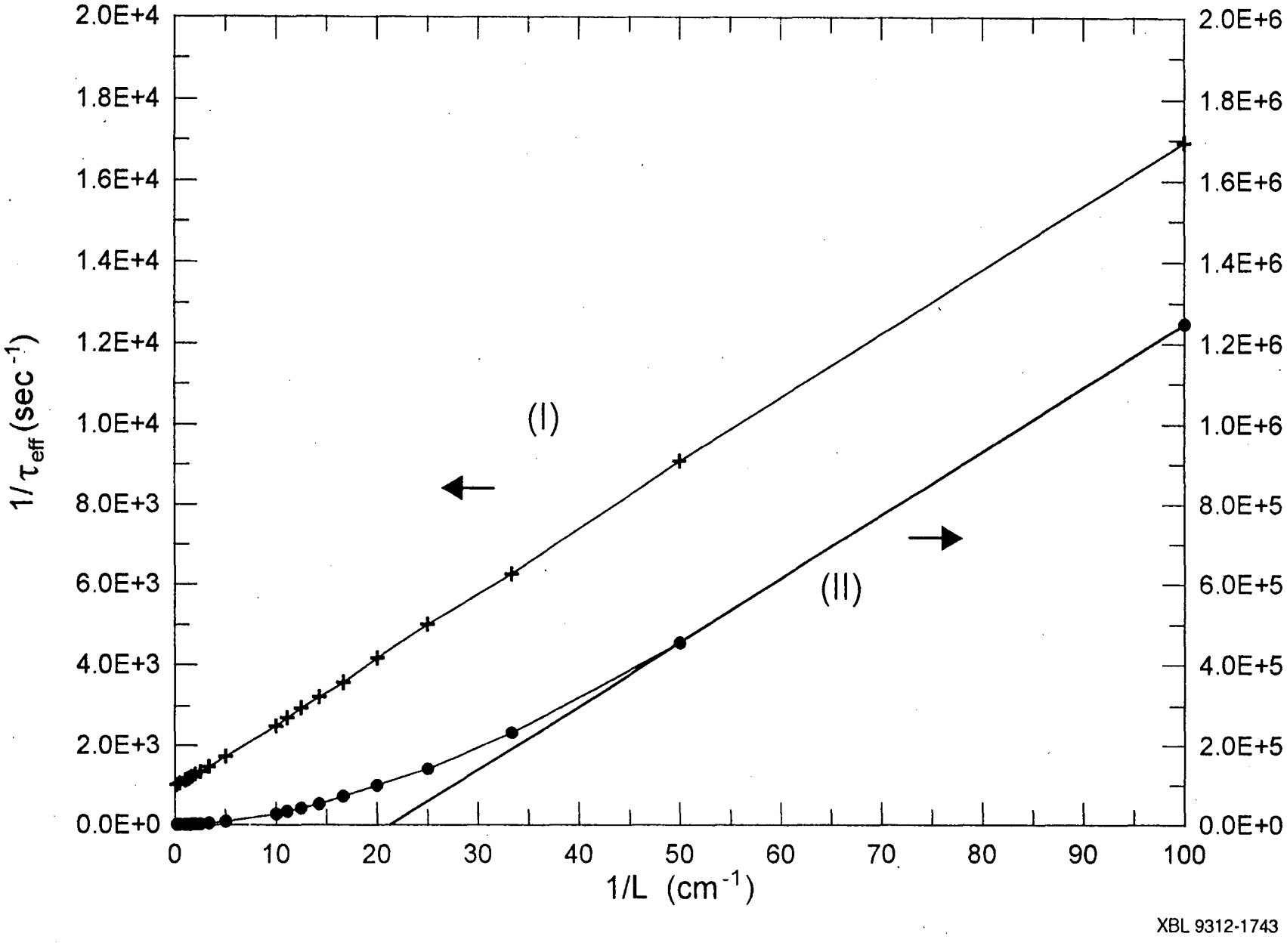

2.0E+4
1.8E+4
1.6E+4
1.4E+4
1.2E+4
1.0E+4
8.0E+3
6.0E+3
4.0E+3
2.0E+3
0.0E+0
$1/\tau_{eff}$ (sec^{-1})
2.0E+6
1.8E+6
1.6E+6
1.4E+6
1.2E+6
1.0E+6
8.0E+5
6.0E+5
4.0E+5
2.0E+5
0.0E+0
0
10
20
30
40
50
60
70
80
90
100
1/L (cm^{-1})
(I)
(II)
XBL 9312-1743

FIGURE 4

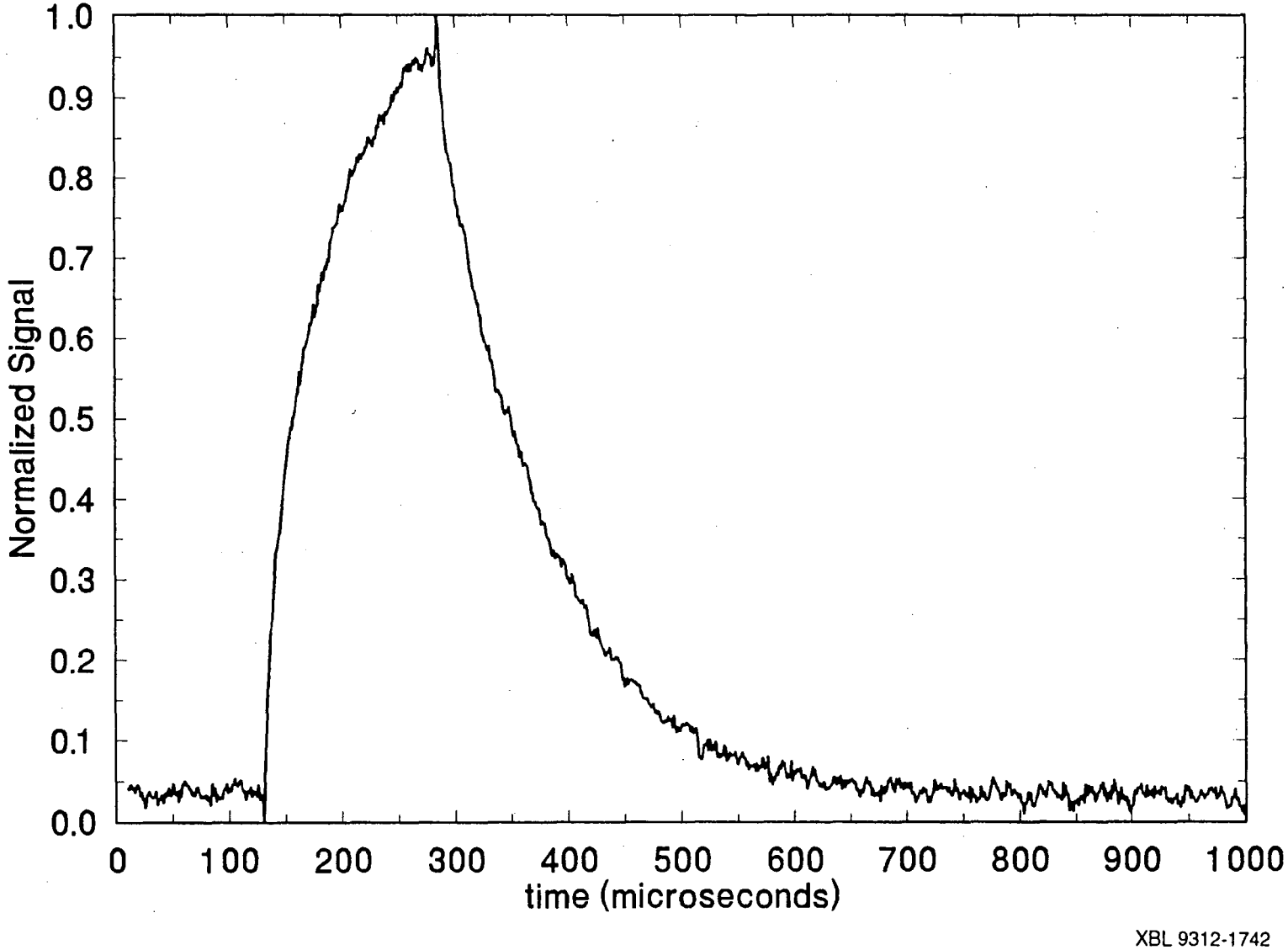

1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Normalized Signal
0
100
200
300
400
500
600
700
800
900
1000
time (microseconds)
XBL 9312-1742

FIGURE 5a

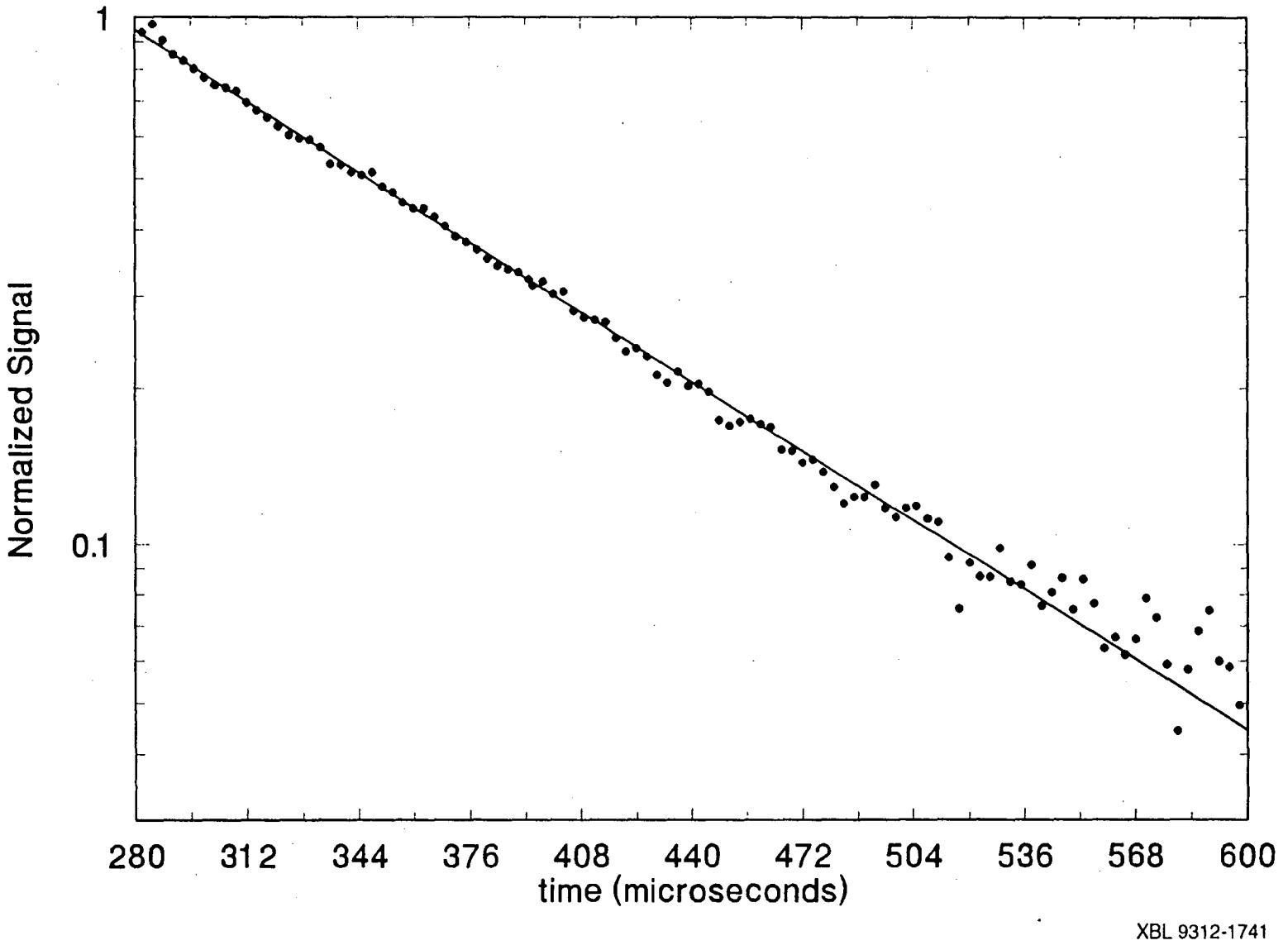

1
0.1
Normalized Signal
280
312
344
376
408
440
472
504
536
568
600
time (microseconds)
XBL 9312-1741

FIGURE 5b

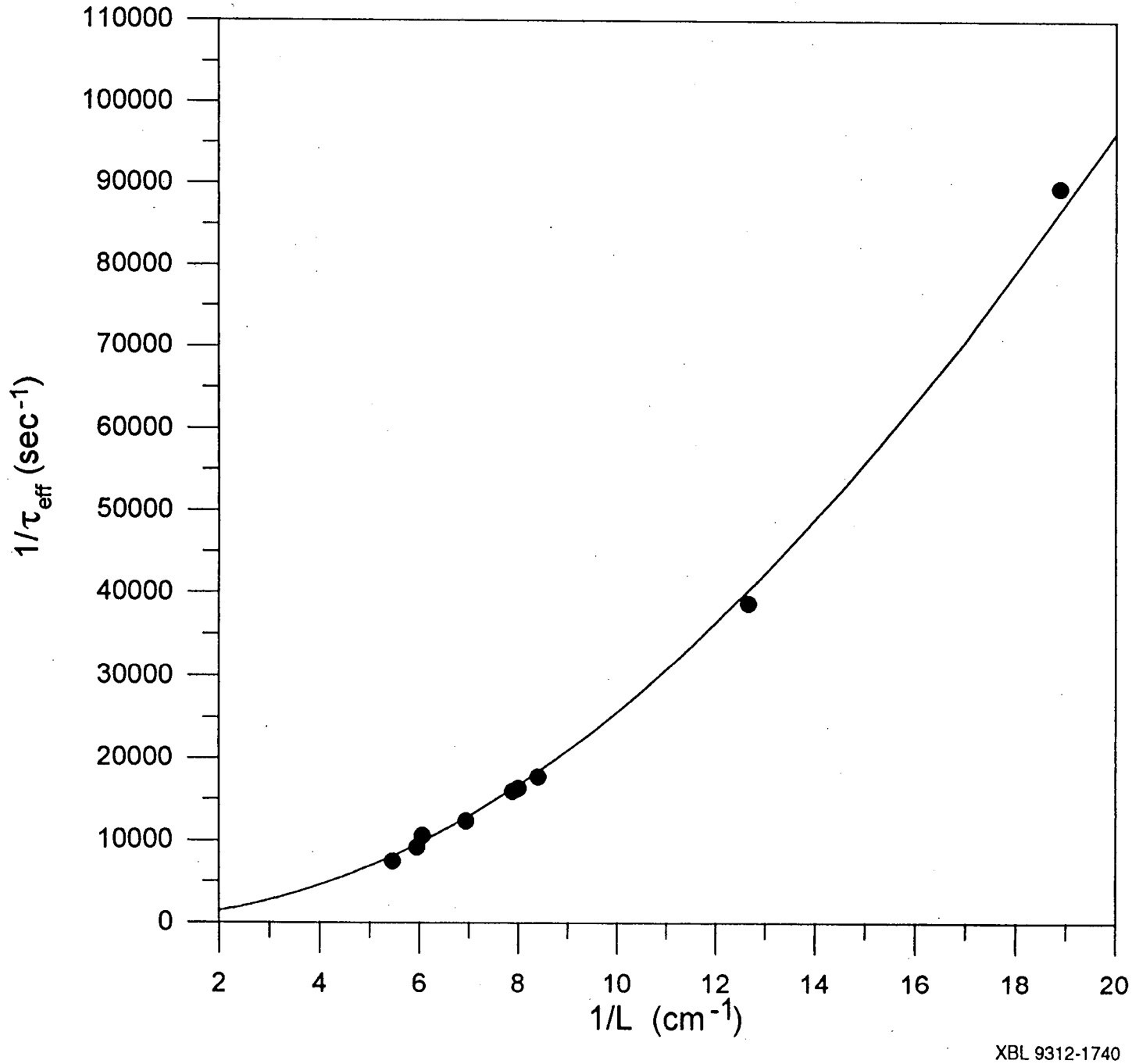

110000
100000
90000
80000
70000
60000
50000
40000
30000
20000
10000
0
$1/\tau_{eff}$ (sec^{-1})
2
4
6
8
10
12
14
16
18
20
1/L (cm^{-1})
XBL 9312-1740

FIGURE 6

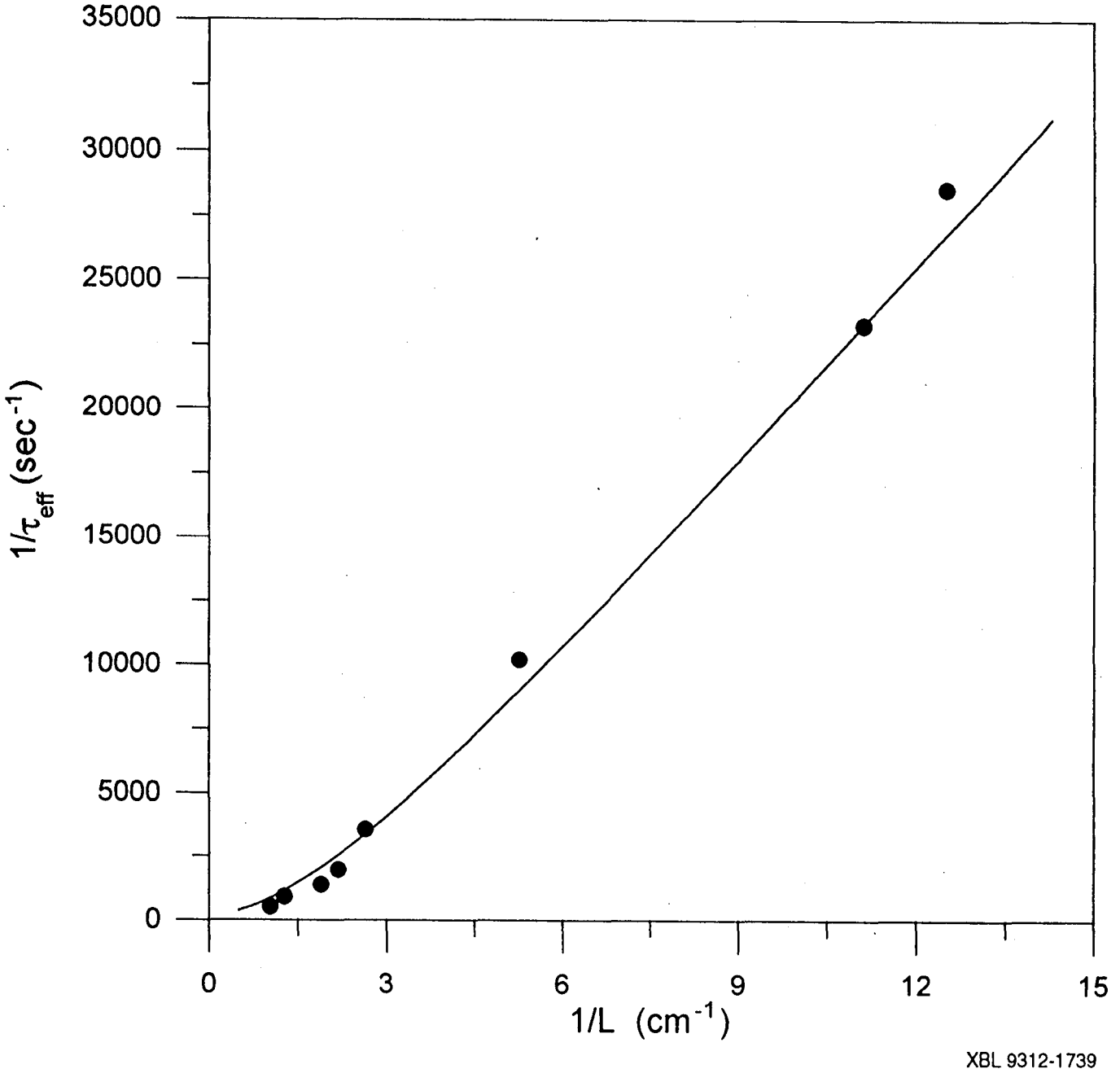

35000
30000
25000
20000
15000
10000
5000
0
$1/\tau_{eff}$ (sec^{-1})
0
3
6
9
12
15
1/L (cm^{-1})
XBL 9312-1739

FIGURE 7

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