

Separation of Carrier Lifetime from Interface Recombination Velocity

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Introduction

The semiconductor manufacturing industry always needs faster, non-invasive means to establish the electrical quality of wafers and processes. Methods to measure and map the quality of full wafers on a routine basis permits faster feedback and identification of problems. Such techniques form a growing part of the statistical Quality Control/Quality Assessment (QC/QA) algorithms of the modern manufacturing process.

In the future, the same requirements will drive the need for non-invasive probes of the electrical quality of thin films. Such films arise in a variety of technologies:

- 1) Silicon-On-Insulator (SOI) is the common technology used for radiation-hardened CMOS circuits, and should provide the low-power, high performance circuits required for the burgeoning needs of portable communications and computers. Such thin films (≈ 30 nm to $\approx 25\mu\text{m}$ depending upon the technology) place extra constraints upon QC/QA technology, both in separating signals of the film from that of the substrate, and also in sheer sensitivity to both the small signal and the short effective lifetime of such a thin film.
- 2) Flat panel thin film technologies are a likely component of High Definition TV (HDTV). The same sensitivity issues arise as in SOI. The current materials technology expected in this arena is amorphous or polycrystalline silicon, in contrast to the single crystal silicon used in the high performance CMOS technologies. Lifetimes for such material will of course vary with thickness, but a value of tens of nanosec has been observed with the present system.
- 3) Power Electronic Building Blocks (PEBB) are an exciting development in power handling, conversion, and control. Many of the technologies for meeting these rather challenging requirements involve bonding wafers. Unlike the bonding technologies applied to SOI materials, in these cases the bonded interface resides *in the active region of the device*. Non-destructive characterization of the recombination velocity at this interface may be necessary for wafer qualification.
- 4) Many technologies require such compound semiconductor wide band gap semiconductors as SiC and GaN. These materials appear attractive for such requirements as high temperature operation and blue light sources. They are also candidates for the Power Electronic Building Block programs. These materials require much improvement in their material quality, and are often grown on or bonded to dissimilar substrates such as silicon ("compliant substrates"). Conventional systems cannot probe the wide gap materials, since the low-energy photons are not absorbed and the decay times are too short; our system meets both requirements, and should provide a useful QC/QA tool for these materials.

- 5) There are other promising technologies that our system may help develop. Thin film organic electronic materials are a promising future mass production technology. Finally, high temperature superconductors have been reported to exhibit carrier lifetime in the range of tens or hundreds of nanoseconds. All of these materials may be amenable to QC/QA by the technology we want to further develop.

Phase I Technical Objectives

All of these technologies involve *films*. The results of measurements of films may be dominated by either the properties of the bulk of the film, or by the interfaces the film makes with its substrate (if any) and at its surface. Most measurements comprise a combination of terms of these types. In many cases, similar measurements on bulk wafers also represent a combination of terms, which are dominated by the bulk properties for sufficiently thick wafers. Many technological trends are driving active films to smaller thicknesses. The goal of the present proposal was to develop a non-contact characterization of **both** bulk and interface properties of bulk wafers and of films such as SOI, SiC, etc. As is discussed later in this report, Interface Studies, Inc. has developed a system to measure the *effective* recombination lifetime for silicon films as thin as 50 nm. The utility of this technique would be greatly increased if this effective lifetime could be used to obtain the bulk lifetime within the film and the interface recombination velocities at the film's interfaces.

The major goal of this Phase I effort was to separate the interface recombination velocity from the bulk lifetime of the superficial silicon layer. The use of multiple wavelengths had been discussed for bulk wafers, and could well be used also for thick SOI wafers. We believed that the addition of multiple intensities could add the necessary information to make this approach feasible for a wider range of wafer characteristics; we had already demonstrated that reduced intensity is sometimes required to get proper lifetimes from bulk silicon, and expected the combination of variables to refine the results. We wanted to develop both approaches and compare and contrast their strengths.

In essence, we wanted to study carrier recombination as a function of initial excitation, both in terms of depth distribution (wavelength dependence) and photon intensity (with respect to interface state densities). We expected the combination of variables to permit us to separately determine "bulk" lifetime within the film as well as interface recombination velocity at both interfaces. The basic impact of wavelength is absorption depth: By altering the wavelength, we alter the initial carrier distribution, thereby altering the carrier decay kinetics until fully equilibrated. This has been done for bulk wafers. Besides extending the absorption length to much smaller values than previously used, we added the variable of light intensity: We have observed strong indications that our intensity is sufficient to saturate interface states, thereby reducing initial recombination velocity. We expected to use the intensity dependence of the initial apparent lifetime as a separate means to determine bulk decay time.

The specific tasks to be performed included

1. Addition of Multiple Wavelength Capability to our System
2. Computer Simulation of the Measurement to Determine Optimal Settings
3. Testing of SOI and Bulk Materials
4. Methodology Development for Separation of Terms

The last task was the purpose of this effort. It has proven much more difficult than anticipated to achieve this goal for the thin ($\sim 2000\text{\AA}$) Si films of most interest to this program. What follows is a chronological discussion of the efforts made for each task under this contract to meet this final goal. The final results, while incomplete, are far more promising than current theories [see, e.g., references 1 - 4] would suggest.

Progress

Task 1: Multiple Wavelength

We briefly discuss the overall experimental technique to provide context for the following discussion. A schematic diagram of the apparatus is shown in Figure 1. The specific approach used is to impinge a pulse of photons upon the sample which excites carriers within the silicon. The wafer sits on an RF resonator, whose "Q" factor is altered by the change in resistance of the sample due to these excess free carriers. For photons of energy greater than ≈ 3.5 eV, all photons will be absorbed in the topmost $\approx 1000\text{\AA}$, so all carriers will be generated in this layer. If the insulating layer is impervious to those carriers, they are all confined to remain in that layer, so the decay time of the excess conductance due to those excess carriers will tell us the effective lifetime of those carriers. This effective lifetime depends upon the electrical quality of the silicon in which the carriers reside; the observed value will also depend upon the quality of the interfaces (the interface recombination velocity) since the silicon layer is very thin. By using a pulsed laser source we obtain larger signal and can measure shorter lifetimes than were possible in previous attempts to perform this measurement on SOI samples [Ref. 5]. The present apparatus uses a pulsed nitrogen laser with a pulse width of order 10 nsec. The primary wavelength of the laser is 337 nm, which corresponds to an energy of ≈ 3.6 eV.

We upgraded our pulsed nitrogen laser by adding a dye laser attachment and dyes for operating at 500 nm and at 980 nm for testing at widely varying absorption depths. We will discuss results from this system under the discussion of multiple exponential analysis.

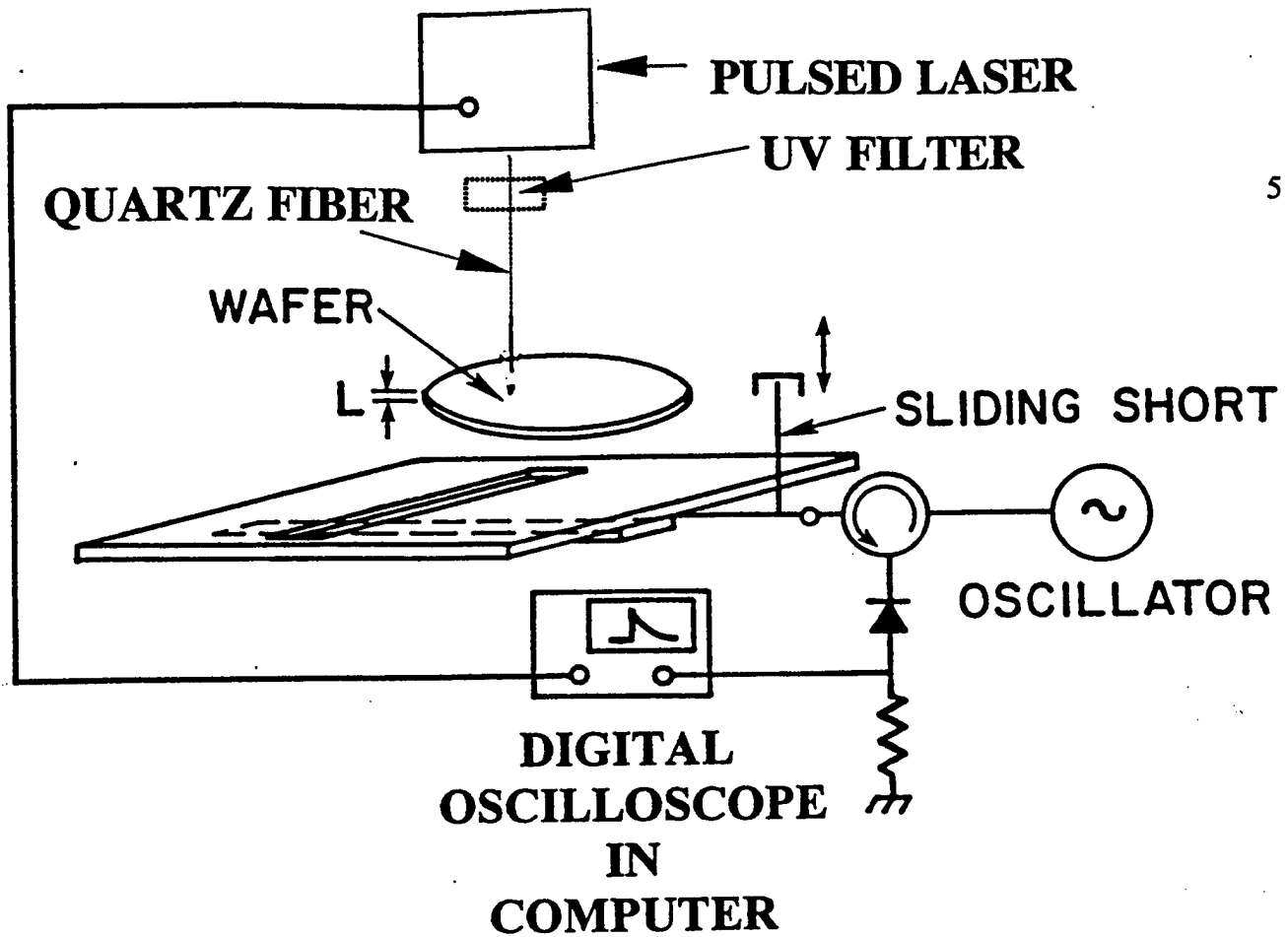


FIGURE 1. Schematic illustration of experimental layout.

Task 2 Simulations

We performed our simulations using a commercial finite element device simulation package on an upgraded personal computer. The simulation package [Ref. 6] was developed by an expert in solar cells who uses the microwave lifetime technique to characterize solar cell material. It contains both the electrical and the optical response of silicon, and hence appears ideal for our purposes. The results confirmed some of our initial expectations:

1. In simulations we noted that the identical bulk lifetime did not lead to the same decay times for films of different thickness -- even when surface recombination was set to zero. This was found to be due to high level injection effects on Auger recombination. An example is shown in Fig. 2. Note that the impact of a *higher* power density (i.e., a constant power absorbed by a thinner wafer) is a *shorter* lifetime. In contrast, our observations have been that a higher power density leads to a *longer* lifetime, suggesting another mechanism at work; we believe this to be saturation of surface states leading to reduced interface recombination velocity. In Fig. 3 we show a similar simulation at a lower power level; note the decay curves for different wafer thickness are now identical. At least for Auger recombination terms, this level of intensity (≈ 0.01 sun, or 0.001 W/cm^2) permits measurement of "low injection level" lifetime for wafer thickness $\leq 1 \mu\text{m}$.

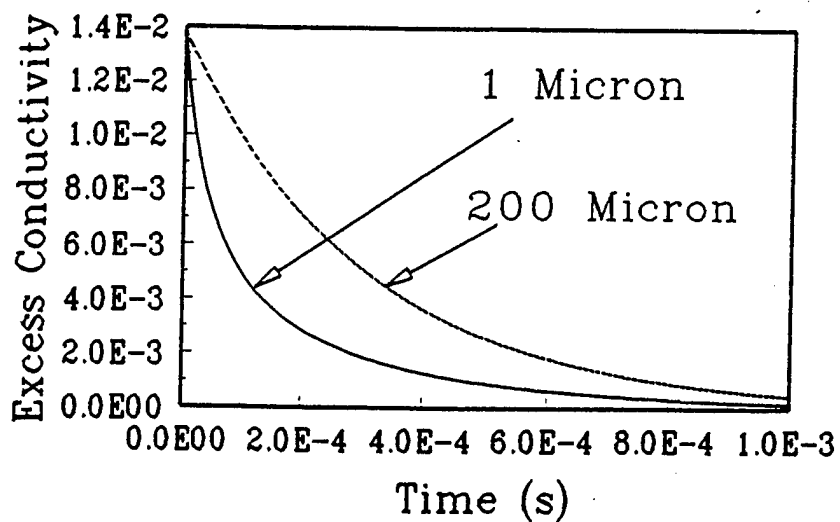


Figure 2. Simulation of decay at high power levels (≈ 1 Sun, 0.1 W/cm^2) for two wafer thicknesses. Wavelength of exciting photons is 336 nm , $\tau_{\text{bulk}} = 1 \text{ ms}$, recombination velocity at both interfaces is zero ($S_1 = S_2 = 0 \text{ cm/s}$).

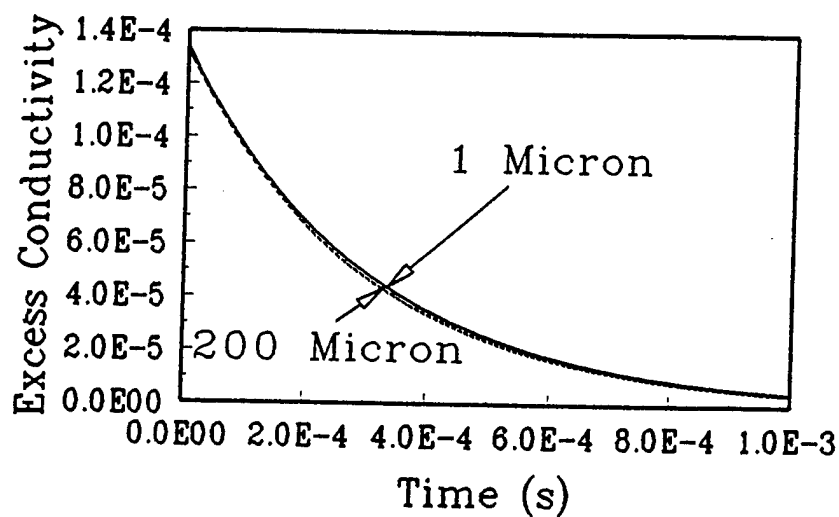


Figure 3. Simulation of decay at low power levels (≈ 0.01 Sun, 0.001 W/cm^2) for two wafer thicknesses. All parameters except power are the same as in Figure 2.

2. For a 20 μm film and at a single, low injection level, we can differentiate between a decay due to *bulk* lifetime of 50 μs (with *no* interface recombination) and decay due to interface recombination of 101cm/s (and bulk lifetime of 1 ms), even though the final decay rates are similar. These results are shown in Fig. 4, and are not dependent upon exciting wavelength. Note that even at this thickness the differences are not large. For thinner films we expect to require more information.

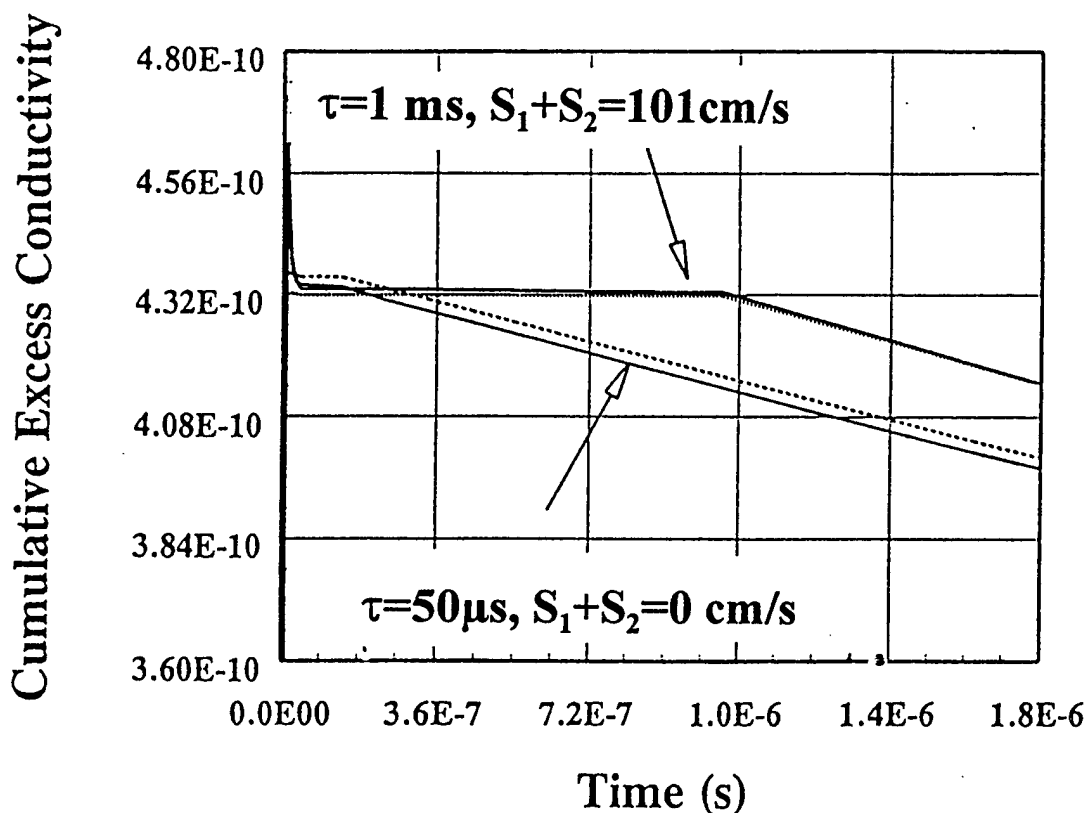


Figure 4. Simulated decay curves at two wavelengths for two different combinations of bulk and surface recombination, both leading to identical decay lifetimes. The solid curves are for $\lambda=336\text{nm}$, whereas the dashed curves are for $\lambda=1000\text{nm}$. All curves are for a 20 μm thick superficial silicon layer.

3. Further simulations on thinner films ($t \leq 2\mu$) led to more discouraging results, as shown in Fig. 5. High intensities gave results indicative of Auger recombination, not bulk lifetime, whereas low intensities (as used for Fig. 4) gave results dominated by the surface recombination terms. As shown in Fig. 5, neither varying excitation wavelength nor the location of the dominant recombination term permitted any discrimination in the decay terms. Our best judgement, based upon these simulations embodying our best understanding of this measurement, was that some other variable was required.

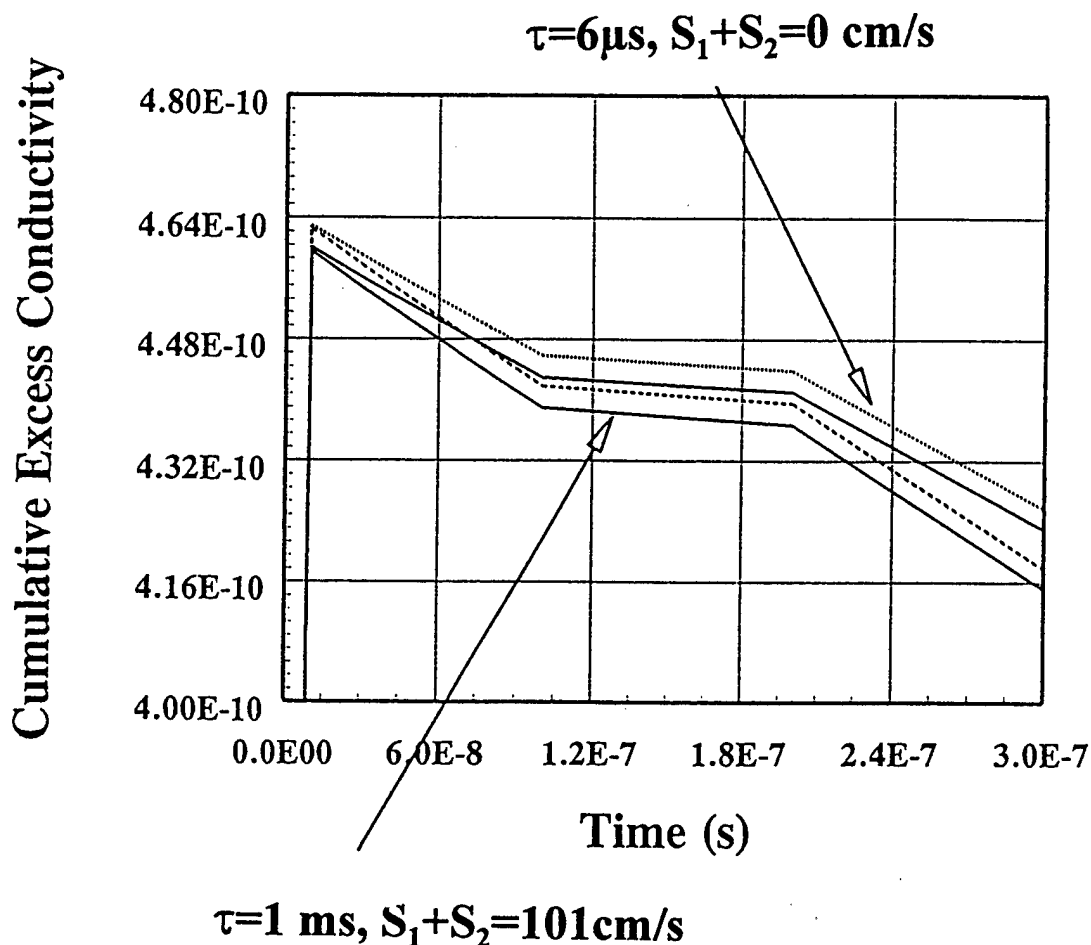


Figure 5. Simulated decay curves at two wavelengths for two different combinations of bulk and surface recombination, both leading to identical decay lifetimes. The solid curves are for $\lambda=336\text{nm}$, whereas the dashed curves are for $\lambda=1000\text{nm}$. All curves are for a $20 \mu\text{m}$ thick superficial silicon layer.

Under this context we noted a paper by Yablonovitch *et al* [Ref. 7] in which the photoconductive decay is measured from a bulk silicon wafer under bias. It was shown that this bias impacted the recombination velocity, thereby altering the observed decay lifetime. In our simulations, similar effects were noted: As shown in figures 6 & 7, a 0.2μ film under different biases will show an *enormous* range in effective decay times. We decided to pursue this option. The results will be discussed under Task 4. However, we note that they were not very successful.

Various analytical efforts to perform the separation discussed here have been discussed in the open literature. In particular, Rozgonyi and co-workers [Ref. 1] have pursued the multiple wavelength approach discussed here. A different effort [Ref. 2] attempts to analyze a single decay curve to perform this separation. All of these efforts are based upon some version of the solution to a one-dimensional minority carrier diffusion equation for a system in which the initial carrier distribution is defined by the time duration and wavelength shape of the exciting light pulse. The resulting diffusion equation is [Ref. 3]

$$\text{Equation 1} \quad \partial n/\partial t = D \partial^2 n/\partial x^2 - n/\tau_b,$$

where n is the carrier concentration, t is time, D is the carrier diffusion coefficient, and τ_b is the bulk carrier lifetime. The solution to this equation requires boundary conditions, namely the initial carrier distribution left by the exciting photon pulse and the recombination velocities at the two boundaries. The solution is a linear superposition of the form

$$\text{Equation 2} \quad n(x,t) = \exp(-t/\tau_b) \sum \{ A_n \exp(-\alpha_n^2 Dt) \cos(\alpha_n x) + B_n \exp(-\beta_n^2 Dt) \sin(\beta_n x) \}.$$

In these equations α_n and β_n are solutions of the transcendental equations

$$\text{Equation 3} \quad \tan(\beta_n d/2) = -(2D/Sd)(\beta_n d/2) \text{ and } \cot(\alpha_n d/2) = -(2D/Sd)(\alpha_n d/2)$$

where d is the wafer thickness, and S is the recombination velocity (assumed equal at the two interfaces). Note that in these equations the effective (observed) decay constant τ_{meas} is obtained from the relationship

$$\text{Equation 4} \quad 1/\tau_{\text{meas}} = 1/\tau_b + 1/(\alpha_n^2 D).$$

As discussed in Boulou and Bois [Ref. 4], the lowest harmonic term in $\alpha_n^2 D \approx d/2S + d^2/\pi^2 D$. A simple understanding of these terms is that the first ($\approx d/2S$) dominates when limited by recombination velocity, and the second ($d^2/\pi^2 D$) dominates when limited by carrier diffusion to the interfaces. For sufficiently thin films and a one dimensional model, diffusion cannot be the limitation, which means that $1/\tau_{\text{meas}} \approx 1/\tau_b + 2S/d$. This is the model typically used, and was relied upon in our earlier work [Ref. 5]. Note that for thin ($\approx 2000\text{\AA}$) silicon films, a recombination velocity of even 2,000 cm/s implies a maximum observable decay lifetime of ≈ 5 ns. It is *crucial* that the surface(s) be passivated for minimum recombination velocity to prevent the signal from being of such short duration as to be unobservable.

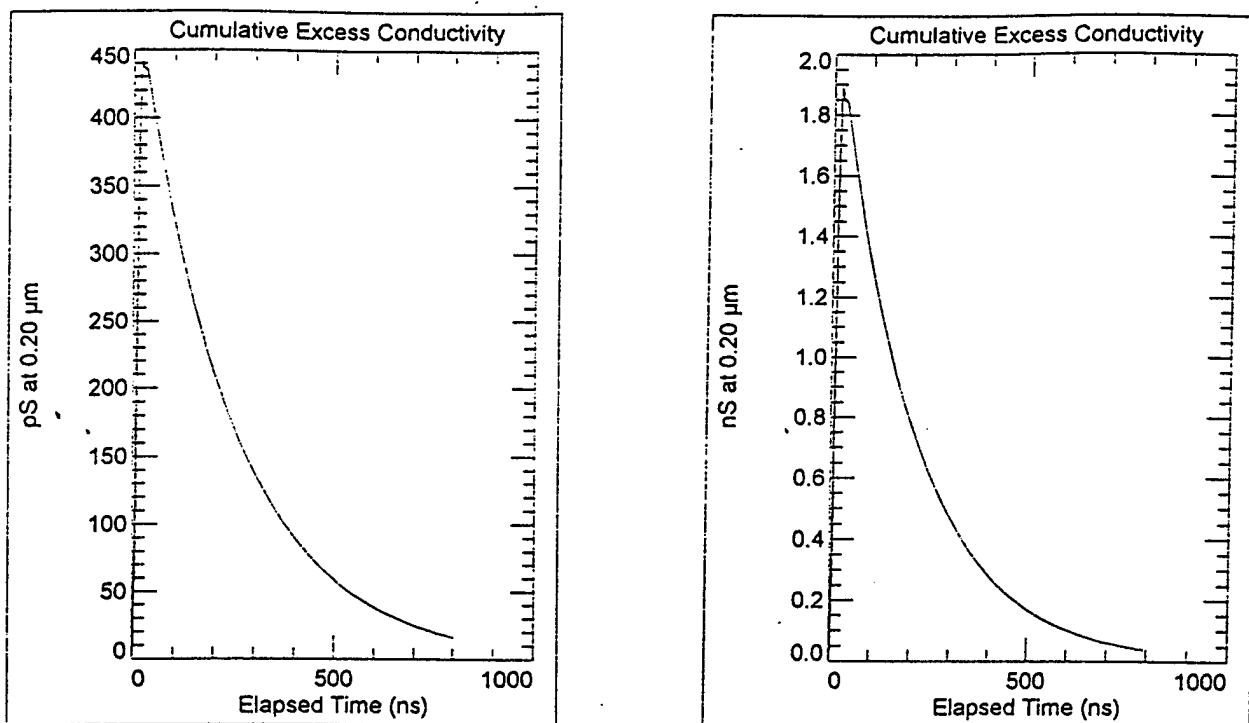


Figure 6. Simulation results for a 0.2μ film under low intensity illumination as a function of bias. Assumed parameters include $\tau=0.6\mu\text{s}$ and front and rear surface recombination velocities both are small ($S_1 = S_2 = 1 \text{ cm/s}$). From left, the applied bias is $+0.5$ and -0.5V .

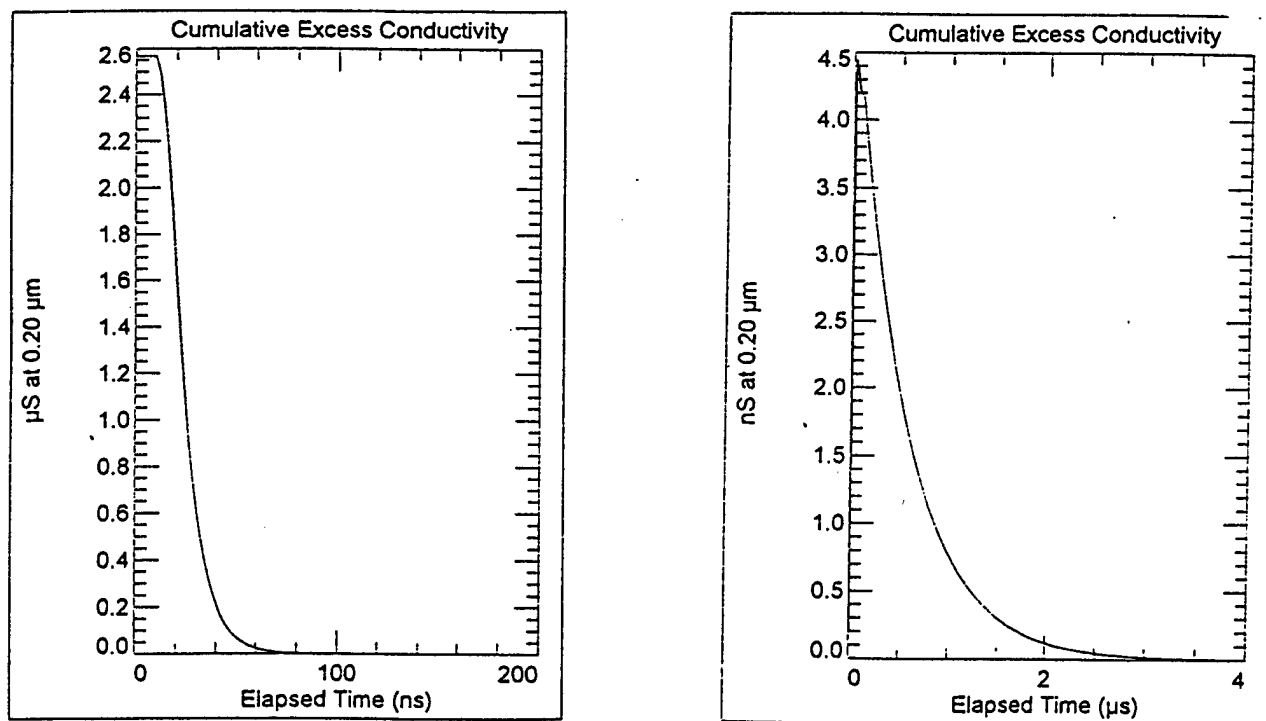


Figure 7. Simulation results for a 0.2μ film under low intensity illumination as a function of bias. Assumed parameters include $\tau=0.6\mu\text{s}$ and larger rear surface recombination velocity ($S_1 = 1, S_2 = 100 \text{ cm/s}$). From left, the applied bias is $+0.6$ and -1V . Note the change in scale on the time axis.

The work of reference 2 depends heavily upon a computer program based upon these standard descriptions of the carrier decay and the observation of more than one decay time. It **requires** that the observed decay curves be composed of many separate exponential decays, as is in fact derived in the standard treatments [Ref. 3] of the decay process we just described. We began to implement this procedure. As part of that process, we had to analyze our curves for multiple exponential terms. Our results will be discussed later, as they led to a promising series of results. However, it must be noted here that our results are **NOT** consistent with the standard theory of decays. For example, we observe a ratio of long life to short life that is outside the realm of possibility within these theories. The series analysis of references 2 and 3 anticipates a fundamental term that dominates the series, whereas our observation is a term that is a small fraction of the normal terms. The origin of this term is not yet clear, but its existence and properties appear promising. It does **NOT** appear in analysis of simulated decay curves. For this reason, our simulations did not suggest this approach to be feasible. Our best guess at this point is that this term is due to patch effects, i. e., the non-uniform distribution of recombination velocities at the two interfaces. It should be noted that lateral distances can be larger than the wafer thickness, leading to diffusion-limited transport between low-recombination-velocity regions and high-recombination-velocity regions. We shall discuss this issue more when we present the results that stimulate this discussion in Task 4.

Task 3 Testing of Materials

During the course of this effort we performed various studies of different sources of SOI material from different sources. One point of this effort was to determine the utility of our standard technique for different types of material. A summary of these results follows.

One of the goals was to test passivation techniques, which -- as we mentioned earlier -- are crucial to these results. These techniques are most easily studied by measurements of bulk wafers. We performed a test comparing our standard passivation (90 s in 10% HF followed by a 30 s rinse) to a more dilute etch ($\approx 2\%$ HF), which leaves a flatter surface on the (111) plane of silicon. We passivated a bulk wafer using our standard technique, and then etched the same wafer in the dilute solution for 10 minutes, rinsed for 30 s, and repeated the measurement. The results were intriguing: At full intensity, our standard etch was (slightly) better ($116\mu\text{s}$ versus $101\mu\text{s}$), whereas at $1/5$ intensity the order was reversed ($35.6\mu\text{s}$ versus $38.1\mu\text{s}$). This suggests that the intensity dependence of our recombination velocity can be affected by our passivation technique; we may need to study this issue further. Unfortunately, for SOI wafers we need access to the buried interface as well for this approach to be useful.

The passivation techniques of D. Schmidt *et al* (*J. Vac. Sci. Technol.* **B14**, 2812 (1996)) have been tested. A comparison between the standard (30 sec HF at 10%) and the newer, more dilute and lower PH solution including H_2SO_4 on *very* long lifetime float-zone bulk silicon wafers suggested that our standard treatment led to slightly lower recombination velocities.

We performed measurements upon a series of three SIMOX wafers from IBIS Technology Corporation which involved different wafer temperatures during implantation. Previous work at IBIS had established that dislocation density was strongly impacted by this parameter. Our results demonstrated several issues:

1. The results across the wafers were very non-uniform; the variance was 58 - 145 ns (640°C), 45 - 200 ns (590°C), and 19 - 110 ns (540°C) for the three wafers.
2. The lowest temperature wafer was clearly the worst, while the other two were similar within the scatter. The average values over the wafer were 101.2 ns (640°C), 105.4 ns (590°C), and 78 ns (540°C).
3. For the same series of wafers, the dislocation densities were previously found (by Ibis) to be $\approx 8 \times 10^7 / \text{cm}^2$ (640°C), $\approx 3 \times 10^7 / \text{cm}^2$ (590°C), and $\approx 1 \times 10^9 / \text{cm}^2$ (540°C). There is a strong correlation between the dislocation measurements (a destructive microscopic characterization), and the lifetime measurements (a non-destructive technique).

More recently, we measured a higher point density on another SIMOX wafer from the IBIS Technology Corporation. The purpose of this measurement was to see if some correlation between the distribution of lifetime and other aspects of the wafers could be discerned. The wafer map is shown in Figure 8. This has not yet been compared with the distribution of other aspects of the wafer measured by IBIS for wafers prepared in a similar fashion.

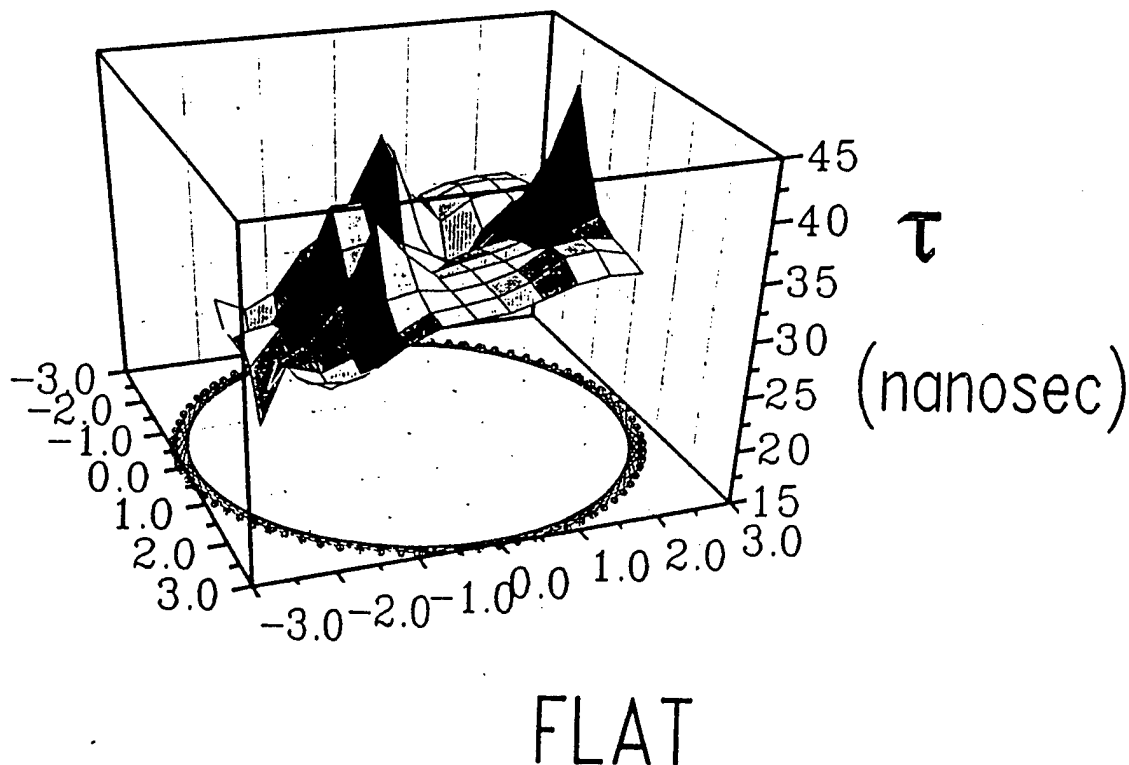


Figure 8. Map of measured effective lifetime results for a standard SIMOX wafer.

Continuing our study of different types of SOI wafers, we have studied several silicon on sapphire (SOS) wafers. Some of the samples gave no observable response, but the thickest sample gave a response, even though it was a standard implant with no special treatment. This sample was the thickest ($\approx 2700\text{\AA}$) of the lot, and, unlike the other samples, it did NOT have the back of the sapphire coated with doped polysilicon, which could have added a conductive term to short out our measurement technique. With assistance from colleagues at Penn State University, we removed the back poly from the other samples; we then were able to obtain a signal from the thickest ($\approx 1900\text{\AA}$) of the remaining samples. In both cases the lifetime observed was of order 3 nanosec, basically the minimum decay time observable with our system. This is the shortest lifetime we have observed. This result is shown in Fig. 9.

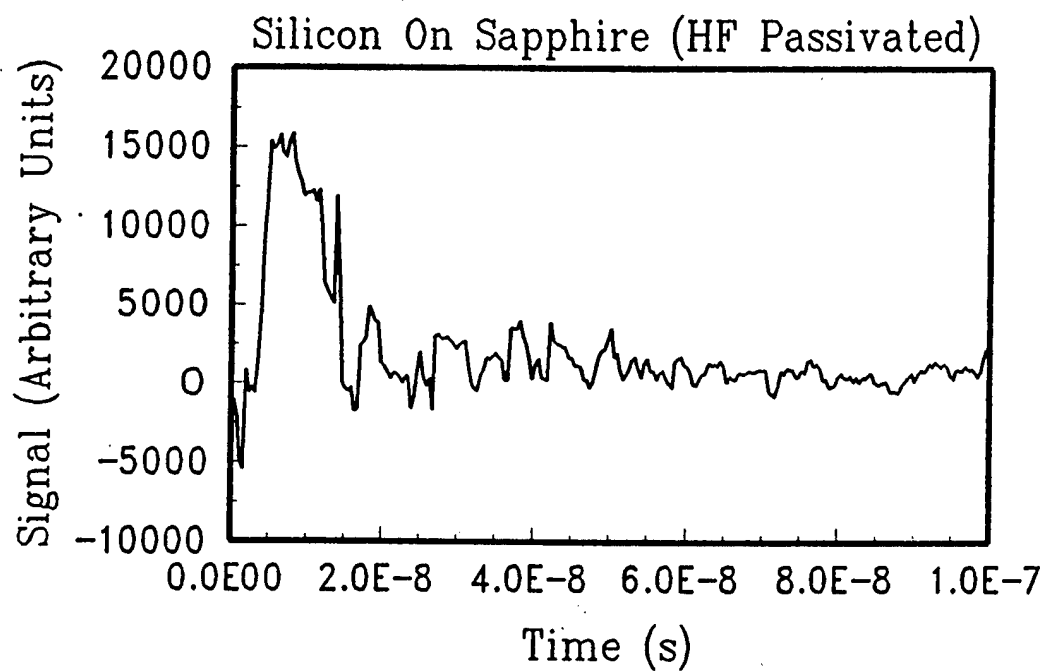


Figure 9. Measured effective lifetime results for a standard Silicon on Sapphire (SOS) wafer. Note that the measured time scale is limited by the laser pulse, not by the sample response time.

Task 4 Separation of Terms

- *Multiple Wavelengths*

The first experimental study of different behavior of carrier decay was performed on a bulk silicon wafer at various wavelengths. As shown in Figure 10, there are clear differences in the behavior of the decay in the early stages for this bulk wafer. These results are as measured, so the differences in intensity are $\leq \times 2$. It is those differences in decay that were exploited by Rozgonyi's group in reference 3 for the separation of terms. As we showed in the first few figures, however, this term, small even for bulk wafers of thickness $\sim 400\mu$, is barely discernible for wafers of thickness $\sim 20\mu$, and clearly not observable for films of thickness $\sim 2\mu$ or less.

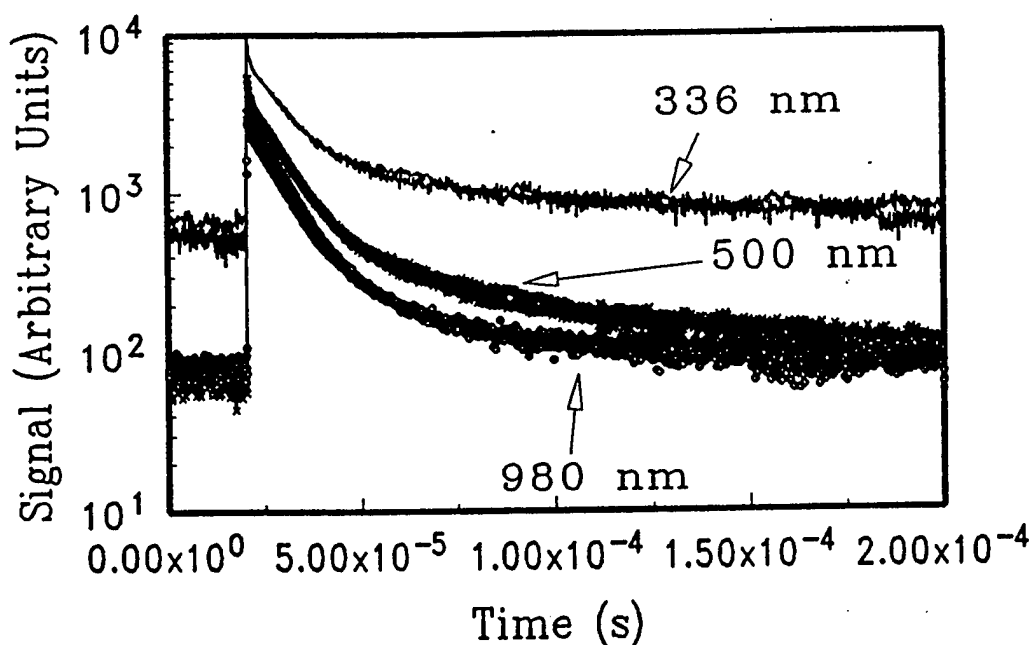


Figure 10. Measured effective lifetime results for a standard float zone bulk silicon wafer with no passivation. The measurements were performed at three wavelengths as shown.

- *Bias Effects*

As mentioned in the discussion of simulations, these models discouraged us from direct attempts to use only intensity and wavelength on these samples. The first approach, using applied bias, was found promising by simulations and was therefore pursued experimentally on thin SOI samples. Before performing these studies we had to establish a satisfactory measurement approach. We did not want this measurement to be a destructive, contacting measurement, so we needed to perform it in a non-contact manner. That meant we needed a separate, transparent conductive film to apply the bias where the light was incident upon the sample. It also meant that the conductor should not be too conductive, or this conductivity would "short out" our measurement. We eventually were provided some suitable metal contacts by Bill Mulligan and Tim Coutts at the National Renewable Energy Laboratory in Colorado. Having the means to apply the front bias, we needed to ensure that the lower bias made it to the SOI film. This meant not only that the SOI wafer could not be oxidized on the substrate, but that we needed to expose the wafer to enough light to ensure that the substrate would conduct the bias to the buried oxide. In Fig. 11 we show the results of a representative study on a SIMOX sample after achieving these requirements.

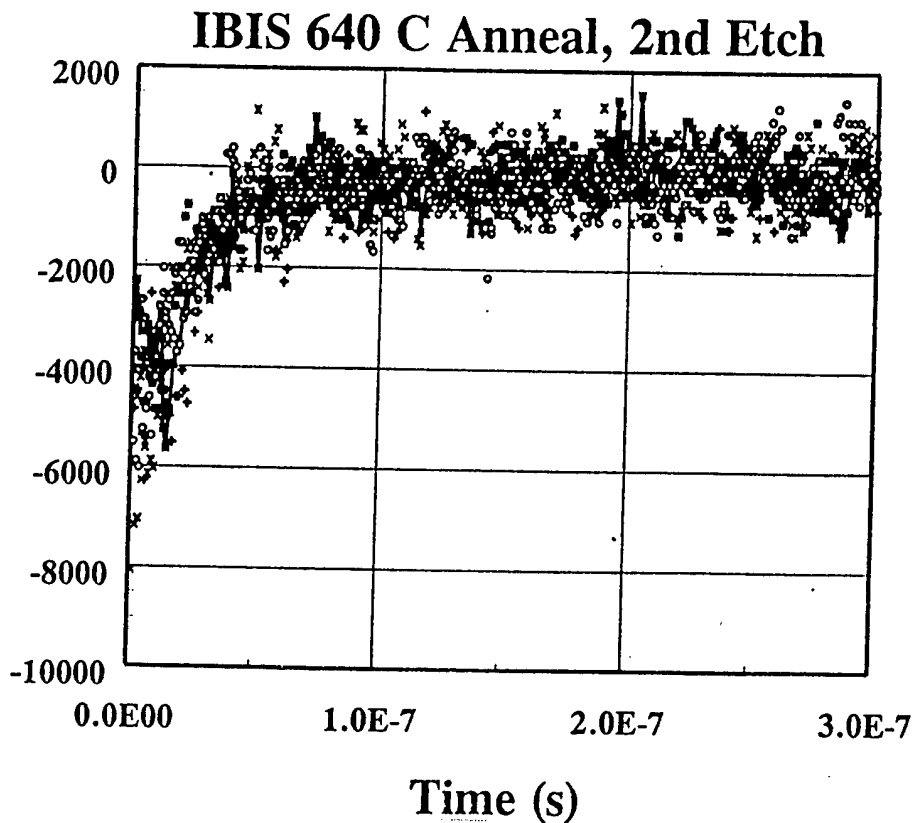


Figure 11. Measured effective lifetime results for a standard SIMOX wafer after HF passivation as a function of bias. The various symbols represent applied bias ranging from 0V to +100V. Note the lack of effect from any applied bias.

As the figure shows, we did not observe the bias dependence we had expected, based upon the simulations. Of course, one of the unknowns in this experiment is the thickness of the air gap between the conductor and the SOI film; this thickness, plus the charges at the various interfaces, determine how the applied field is apportioned between the gap, the film, the buried oxide, and the "handle wafer." All we can say for certain is that we saw no clear signs of the behavior expected from the simulation. The bias was certainly being applied; we often ran at biases sufficient to induce significant leakage current -- which means that substantial bias was applied across the buried oxide, and hence across the superficial silicon layer itself.

On only one sample was this contactless bias able to induce any clear effect. This result is shown in Figure 12. It was on a bonded SOI wafer with an exceedingly low lifetime. This wafer had a silicon thickness of 1000\AA and a BOX thickness of 5000\AA .

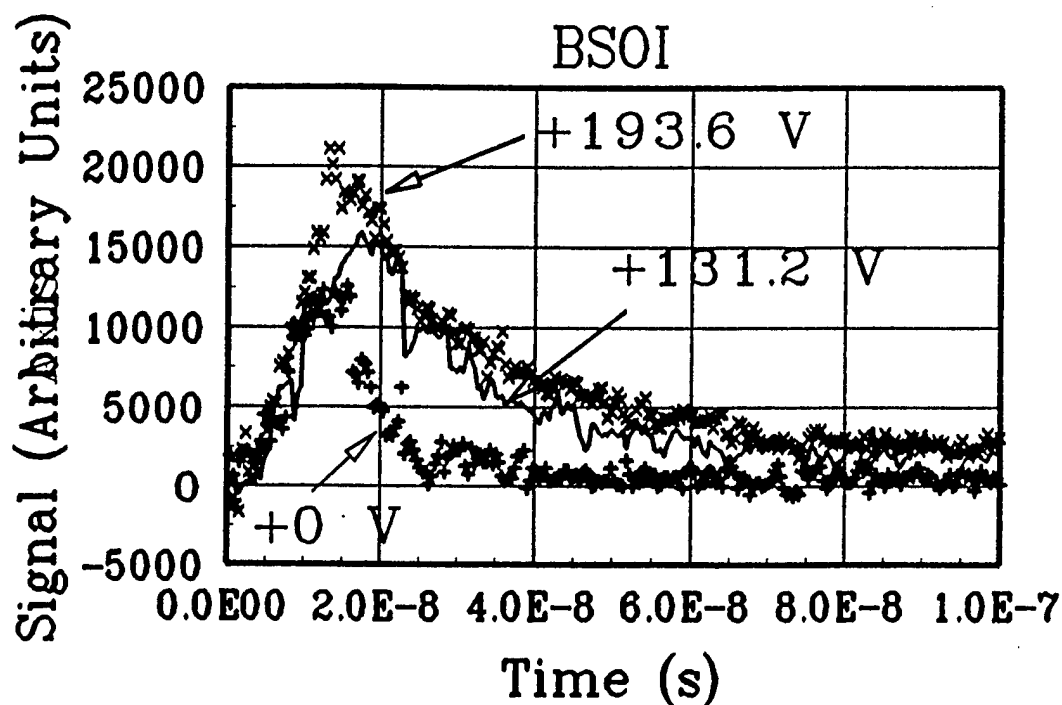


Figure 12. Measured effective lifetime results for a non-standard BSOI wafer after HF passivation as a function of bias. This wafer had a very thin silicon layer ($\approx 1000\text{\AA}$) and a very thick buried oxide layer ($\approx 5000\text{\AA}$).

Believing that the problem was one of properly applying bias across an air gap to a thin, $\sim 2000\text{\AA}$ silicon layer, we had several SOI samples of various origins oxidized and then had a transparent conductor deposited. Note that this abandoned the hope of a non-contact technique, but we hoped the results would shed light upon the mechanisms of the effects being observed. Again, the metal had to be transparent and partially conducting. In the end, the metal was sputtered on, the resistance permitted measurement, but the sputter-deposition induced such damage across the 200\AA oxide that the lifetimes after metal deposition were an order of magnitude lower than were the lifetimes before deposition.

Believing that a thicker oxide would help, we tried again. This time we grew $\sim 800\text{\AA}$ oxide layers before depositing the metal. The results were improved, but still imperfect. The lifetime was only reduced $\sim \times 2$ from the starting material by the metal deposition. There was still no clear impact of applied bias upon measured lifetime. Thus the bias experiments were abandoned.

- *Two Exponential Extraction*

At this point we began to explore the analysis of Giles and Schwartz [Ref. 2]. The first requirement of their program was that the decay curve be analyzed in terms of **TWO** exponential decay curves, not the single one normally used. This analysis provided the first optimistic results based upon **experimental** work. However, as noted in the discussion of this method, the results are not fully in line with the theory and analysis accepted for photoconductive decay studies.

Let us begin with the results for a simple, straightforward case. We studied a bulk high quality silicon wafer (after air exposure to obtain high surface recombination velocities) at three wavelengths. We attenuated the light pulses for both 336 nm and for 500 nm to obtain similar signal levels at all three wavelengths; given the low level obtained at 980 nm, this means we were attenuating by $\sim \times 1/100$, so we expect to be in the low level regime for this bulk wafer. This data was shown in Fig. 10. The two exponent analysis yielded the results shown in Table I on the next page. The last column, labeled " σ ," is the RMS error for that fit; we present the lowest error for each run as the *first* row. Note that the form of the fit was

Equation 5 $\text{Data}(t) = C1 \exp(-t/\tau_1) + C2 \exp(-t/\tau_2) + C3$

The first comment on these results must be that, like any least squares regression fit, the parameters are a "best fit" within the model, and may be only a local minimum. Furthermore, the minimum is not terribly deep; one can obtain very different results with a least squares error of only 10% larger than that for these minimal values. This is not a terribly strong result -- for a single fit. However, note that these results reproduce quite well from run to run. Note further that the trends between wavelengths are also consistent. These consistency checks lend some additional credence to these results. The second, longer lifetime of about $70\mu\text{s}$ is smaller than the measured lifetime ($\approx 170\mu\text{s}$) on passivated material, but it does reflect the high quality of the material.

Table I Two-exponent analysis for bulk wafer at three wavelengths

Run	λ nm	C1	τ_1 μ s	C2	τ_2 μ s	σ
Nitro3	336	3467	31.7	120844	6.7	3617333
		1279	291	40480	10.6	5053319
		single	---	23045	14.1	11561538
Nitro4	336	1471	60.6	54843	9	3972998
		1282	209	42952	10.1	4131522
		single	----	21187	14.5	13579620
Dye5	500	578	64.4	39922	8.7	93890
		497	188	33276	9.4	189296
		99	453	21879	11.4	1663928
		single	----	20286	11.8	2065127
Dye6	500	467	70.5	37182	9.1	90105
		392	120	33767	9.5	107330
		single	----	22219	11.4	1553891
Dye7	980	205	76.4	29745	9.1	88728
		492	35.9	34739	8.4	94883
		single	----	21700	10.3	446654
Dye8	980	198	67	23483	9	86033
		186	219.5	21487	9.4	105210
		single	----	16393	10.7	345739

These results are not predicted by current theories of this phenomenon. In particular, the theories of references 2 and 3 anticipate that the strongest decay mode will be the one that exhibits the longest decay time -- the *fundamental mode*. In fact, the ranges accessible for the ratio of C2 (the intensity of the second decay term) to C1 (the intensity of the first decay term) in the program of Giles and Schwartz barely permits this ratio to exceed unity in the parameter range we explored, whereas the observed ratio clearly exceeds 30 for 336 nm and 100 for 980 nm. Furthermore, the decay *time* for a mode is not a function of excitation wavelength within these models; the wavelength and associated absorption length only impact the ratio of amplitudes, not the decay time period. This result is not anticipated by current theory, and was only performed to try a theoretical fit that apparently does not apply.

Given these unexpected results we have studied more of our bulk silicon samples using the 336 nm photons. Some of those results are shown in Tables II and III. These wafers were both high quality float-zone-refined wafers that we had HF-passivated and measured about 6 months prior to the listed measurements. After the "as received" measurements, we then HF-passivated again. Note that for the first wafer the passivated results match exactly with the weaker, longer term in the measurements on the unpassivated wafer. In both cases a τ of about 390 μ s is clearly inferred.

Table II Two-exponent analysis for bulk wafer at different conditions

Run	Sweep	As Received				
		C1	τ	C2	τ	σ
	μs		μs		μs	
H62771A3	1,000	16291	395	209734	26	58815088
		18278	310	192936	3.3	147952340
		26036	1779	275187	29.4	312364118
H62771A2	2,000	12357	390	1208774	31.1	3599603
		13542	362	1593734	2.4	10340058
H62771A1	1,000	9881	365	1485469	17.1	10753781
After HF Passivation						
H7122P1	3,000	68498	393	Single	--	34255141

For the next sample, also a float-zone-refined wafer, the correlation was not as close. However, note that in this case, the passivated sample shows a higher harmonic term in agreement with one-dimensional theories.

Table III Two-Exponent Analysis for Bulk Wafer at Different Conditions

Run	Sweep	As Received				
		C1	τ	C2	τ	σ
	μs		μs		μs	
H62772A3	100	2442	111	66647	11	1325718
		2471	67.1	66918	11.1	1327425
		2511	68.8	67055	11	1345703
		3957	278	66516	11	1357162
		4707	230	69115	11	3624487
H62772A2	500	2931	59	1551667	12.6	1729676
		3823	53	1628236	12.4	1749662
		652	233	1217056	13.4	3546244
H62772A1	200	1221	81	1366529	12.9	9240703
		1121	181	134674	13.1	9431538
		1871	495	133541	13.2	9607866
		3384	1042	133232	13.2	9672450
		2318	381	138361	12.9	11334691
After HF Passivation						
H7171P1	2,000	3478	160	56531	421	27475355
		2533	219	56332	420	29920844
		6326	14.5	58256	413	32785261
H7171P2	2,000	4001	176	58391	353	22344019

We find these results fully consistent with the variations expected of patch effects on these

measurements. We expect the results to be of more use for thin films, where we expect more sensitivity to lateral inhomogeneities in surface recombination velocity. For this reason we analyzed a variety of our SOI wafers, and the analysis is discussed below. It should be mentioned, however, that the depth of these minima is often very slight. Furthermore, the results should still depend upon lateral variations in both bulk and/or surface recombination, and we have no independent measures of these parameters.

First, we analyze the results of measurements of some of the structures with surface oxide and deposited metal discussed earlier for the bias experiments. This analysis offers more intriguing results, as well as the *beginnings* of an explanation for the failure of the series of experiments under bias. This specific samples were a SmartCut™ wafer and a SIMOX wafer, each with $\sim 800\text{\AA}$ of oxide and a thin, transparent metal whose deposition added some interface damage as suggested by reduced effective lifetimes. As shown in Table IV below, the bias-dependent results appear consistent. As the bias grows more negative, the strength of the weaker, longer term increases, as does this second lifetime itself. Note that the absolute strength of this term is always much smaller than that of the dominant term, meaning that the single exponential analysis would not strongly observe this signal. The reduced lifetime (only 11 ns) observed for the largest bias was also observed in the single exponential analysis, and appeared to persist to higher biases, although the noise level called that into some question.

The noise level is another crucial point. The longer term, apparently related to the bulk lifetime, is very weak -- less than 1% of the evident signal. This means that setting the sweep period to a value appropriate to the evident, quickly decaying signal may set the sweep length too short to properly define the full decay. As an example, the results under bias for these wafers were obtained with a sweep length of $\approx 0.3\mu\text{s}$; in this time a $30\mu\text{s}$ decay time would not be strongly distinguishable from a zero offset. Note that the RMS error (σ) varies by an insignificant amount, less than 1%, for widely varying values of the first τ .

Table IV **Biased and oxidized SmartCut™ $\sim 0.2\mu$**

Run	Bias	C1	τ	C2	τ	σ
			ns		ns	
VS520712	+36	-1168	660	-57808	11	201280544
VS520706	.+20	-436	11290	-12864	27	171545650
		-738	13200	-13377	27	171764948
		-658	7500	-12310	28	171845800
VS520713	0	-974	140000	-1670857	9	189509166
		-1040	5204	-161614	9	190022450
VS520710	-30	-632	255563	-88978	11	136025221
		-606	77486	-92652	10	136037803
VS520711	-36	-627	767400	-271313	8	83277072
		-719	26952	-264848	8	83323878

We see a similar lack of sensitivity to the long decay time for a passivated and biased SIMOX sample, as shown in Table V. Note that, for both of these samples, there is apparently a bias dependence upon the observed long lifetime term. However, this term is such a small fraction of the total decay curve that it is not evident without such a detailed analysis.

Table V Biased and oxidized SIMOX $\sim 0.2\mu$

Run	Bias	C1	τ ns	C2	τ ns	σ
VS520720	0	-6.5e9	407	-1.3e11	18.5	1.9609e22
			2900		18	1.9732e22
VS520721	-10	-6.5e9	37288	-1.37e11	18.5	1.9781e22
		-7e9	24300	-1.3e11	16.6	1.3928e22
			339800		16.1	1.4074e22
VS520722	-20	-7.8e9	4032	-1.26e11	16.1	1.4158e22
		-1e10	68900	-1.5e11	11	1.7266e22
			134300		11	1.7271e22
		-1e10	3899	-1.5e11	11	1.7321e22

When we lengthen the sweep, we can regain sensitivity to these decay times. Note the sweep length dependence observed for no bias and HF-passivated samples (Table VI). These are from the same wafers, but are not the same areas as those quoted in the biased results. In these cases, for sufficiently long sweeps, we clearly obtain significant differentiation; the RMS error (σ) can change by 20% or more, a very significant result.

Table VI Two-exponent analysis for SmartCut™ wafer at various sweep lengths

Run	Sweep μ s	C1	τ μ s	C2	τ ns	σ
S70673P1	0.3	205	6.4	-64397	68	33528063
		-74	405	-58361	64	35177992
S70673P2	20 [Ref. 8]	-168	84	-2.15 e15	95	304399
		-256	0.99	-1.22e15	97	365569
		-168	2.1	-6e14	100	442573
S70673P3	3	-1406	2.9	-16296	55	33475694
		-1251	2.3	-16294	55	33567494

In Figure 13 we show the best fit results for run S70673P2, the 20 μ s sweep [Ref. 8] on the

SmartCut Two Exponential Fit

Tau1 = 95 ns, Tau2 = 84 microsec

22

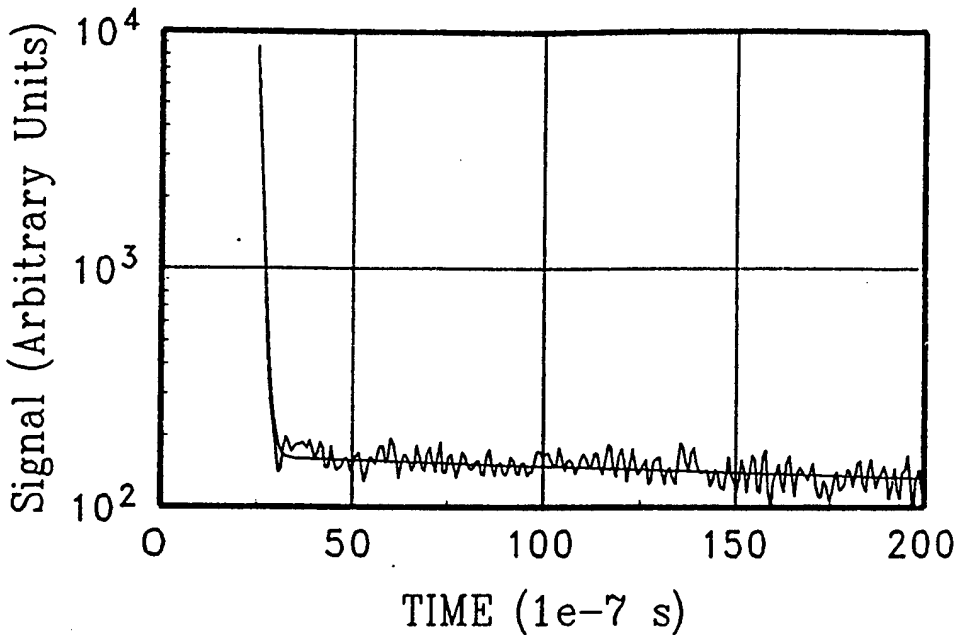


Figure 13. Measured decay curve and best fit for SmartCut™ wafer in 20 μ s sweep. Note the slope of the tail, which is being fit with an effective decay lifetime of 84 μ s.

A similar analysis of a SIMOX wafer suggests a very different “bulk” lifetime (Table VIII). The two independently measured spots both give similar values. The origins of these differences clearly requires more study.

Table VIII Two-exponent analysis on IBIS SOI wafer at various sweep lengths

Run	Sweep	Spot	C1	τ μ s	C2	τ ns	σ	
I70672P1	0.3	2	-509	21.9	-53562	49.4	40354374	
			-507	221	-53338	50	40360367	
I70672P2	20	2	-301	3.5	-6.5e14	100	583304	
			[Ref. 8]	-259	16.1	-3.4e14	103	804358
			-241	328	-4.6e15	93	884154	
I70672P3	3	2	-1425	3	-9335	48	36426903	
I70671P2	20	1	-2373	1.8	-4.5e15	91	224757	
			[Ref. 8]	-2236	1.9	-1.3e15	95	301037
			-459	5.3	-2.4e15	94	1116569	

Measurements on other sections of HF passivated wafers gave differing results, varying from no signal to $\approx 15 \mu\text{s}$. This could indicate that we measure an artifact of noise, or it could be due to variations in wafer quality and HF passivation. We tested this by measuring the set of oxidized and metallised wafers twice. Those results follow in Table VIII; the two columns of τ Front correspond to two independent measurements on the same sections of the same wafers. The agreement is quite satisfactory. Note that the results for these oxidized SmartCut samples ($\approx 6 \mu\text{s}$ & $34 \mu\text{s}$) exhibit a range consistent with the (higher) value of $\approx 84 \mu\text{s}$ found for an HF passivated piece from the same wafer in the table of page 20. Similarly, the results for an oxidized SIMOX wafer ($\approx 6 \mu\text{s}$) are consistent with the value $\approx 3.5 \mu\text{s}$ (for an HF-passivated piece from the same wafer) found in the table on page 21. As an aside, in the present table we minimize problems with the fit by fitting to a *single* exponential. We do this by fitting only to data after the rapidly decaying function has disappeared.

Run	Sweep μs	τ Front μs	τ Front μs	τ Back μs
(SmartCut Piece # 1)				
S71871m2	100	5.8	6	
S71871m3	100	6.7	---	
S71871b4	100			11.5
(SmartCut Piece # 2)				
S71872m1	100	36	32	
S71872b3	100			16.5
(SIMOX # 1)				
I71873m1	20	7.7	5.1	
I71873B4	50			2.3
(BESOI)				
H71874m1	20	1	Not measured	
H71874B3	50			0.7

One further piece of information is included in this data: The lifetime measured on the *back side* of the wafers. Note that the SIMOX result is quite low, and the result for the old BESOI is even lower. The lifetimes measured for the backside of HF passivated SmartCut wafers has ranged from ≈ 15 to $\approx 40 \mu\text{s}$. The lifetimes for several SIMOX wafers from Ibis were all found to be $\approx 2.5 \mu\text{s}$, which is very low. At least one SIMOX wafer from a different source gave a backside lifetime at least twice that value.

Discussion

These results are optimistic. They strongly suggest that we can directly observe decay times characteristic of the material quality of the superficial silicon layer, with no extra data treatment

required. The limitation is that this feature is not currently a universal characteristic of all measurements of this material. It is our expectation, however, that further improvement in material quality will lead to increased applicability of this interpretation.

However, we cannot claim to have fully proven all results. In the absence of a well-defined and well-supported theory of these results, experimental results need to be iron-clad prior to full acceptance. Furthermore, the analysis remains incomplete: While we are measuring something between the recombination-mediated decay and the bulk decay, the mechanisms that engender this effect are not yet fully demonstrated. As we mentioned earlier, we believe that the most likely origin of these results is a "patch effect," that is, the result of the fact that the recombination velocity will not be uniform over the interfaces of the wafer.

As noted in other discussions of "patch" effects [Ref. 9], the impact of these non-uniformities will depend upon the measurement technique and the relevant length factors. In the present case, a relevant scale factor is the thickness of the layer being probed. Recalling our earlier discussion in which the wafer thickness, when small, will cause interface recombination to dominate the effective (measured) decay lifetime, we note that regions of small recombination velocity will alter that conclusion if they are unable to diffuse to a more rapid recombination velocity in the appropriate time. That is to say, if an interface recombination velocity varies over a finer scale than that of the wafer thickness, then the distribution will average out within the wafer *via* lateral diffusion within the wafer. However, if the distribution variations occur over a distance scale large compared to that of the wafer thickness, then these variations can play a substantial role, since diffusion processes cannot proceed as quickly over the lateral dimensions (assumed large) as they can over the wafer thickness dimensions (assumed small). By this logic, a region within the excited area containing unusually low recombination velocities that is somewhat isolated on a scale of the wafer thickness could lead to these results. This is difficult to expect on a scale appropriate to a 500μ wafer, but may become more prevalent on a film of thickness $d < 0.2\mu\text{m}$. We note that interface state density at well-defined silicon-oxide interfaces had dropped to $\approx 10^8\text{cm}^{-3}$ fifteen years ago [Ref. 10]. This density corresponds to an *average* of 1 state/ μ^2 , and suggests that gate quality oxide interfaces on both sides of a film of thickness $d < 0.2\mu\text{m}$ should not exhibit the thickness-limited single exponential decay, but the more complex decay curves we are postulating.

We must conclude that, at this point, this effect does not appear to be an experimental artifact. Our tests of all the experimental artifacts we could think of were negative; the results were not due to any artifact we tested. While the signal level is small, the last table shows that it is of sufficient magnitude to be reproduced, and Fig. 13 demonstrates that the signal is clearly visible, not an artifact of analysis. If this signal arises from some small non-linear response in our apparatus, it still appears useful and should be pursued regardless of origin. We tested one sample at various settings of the tuning short -- which can alter and distort measured line shapes if set improperly -- and were unable to impose or alter such a long decay curve. We have tested both the SIMOX and the SmartCut wafers front and back. The values we obtain cannot be ascribed simply to measuring the substrate lifetime. Furthermore, we have performed some of these measurements using a filter to remove any possibility of even 0.01% of the light reaching the

substrate unless there are defects that microscopic analysis on similar wafers should have observed.

A side comment is in order. The measured lifetimes for the SIMOX samples are often lower than those for the SmartCut wafers. This discrepancy is clearly established for the backside lifetimes. The variation in frontside results makes this less firmly established, but the preponderance of the results lead to such a conclusion. It is interesting that at least some of the inferred lifetimes for the SOI film are larger than those measured on the backside of the wafer.

Conclusion

We have established the capability of obtaining data at multiple wavelengths and using this information to help separate the impact of surface recombination velocity from bulk lifetime terms. We have performed simulations of many parameters for these structures, and established the conditions under which the simulations expect this technique to work. Since this technique should not work for submicron SOI layers, we sought alternatives. Applied bias appeared likely to work from the simulations performed, but the experimental results were disappointing. Finally, a simple two-exponent analysis offers strong possibilities for success. Future work shall combine the extra long sweep time, two exponential analysis, and applied bias to more fully confirm this analysis. However, we have obtained the beginnings of a methodology for separating these parameters as desired.

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8. Note that the longer decay time region is clearly visible. However, note that even a sweep length of $\approx 20\mu\text{s}$ is inadequate to distinguish well between a decay time of $\approx 84\mu\text{s}$ and of $\approx 40\mu\text{s}$. Note also that the 95ns time is that of the preamplifier; an experimental limitation of my apparatus is that for sweep speeds of $20\mu\text{s}$ or greater, the amplifier time constant limits observed decays to this time. To properly observe shorter decay times, I must operate in a *sampling mode* which can only be done for sweep speeds shorter than $20\mu\text{s}$.
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