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DEVELOPMENT OF PROCESSES FOR THE PRODUCTION OF SOLAR GRADE
SILICON FROM HALIDES AND ALKALI METALS, PHASE II

Fifth Quarterly Report for October 1—December 31, 1980

By
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January 1981

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Phase II

FIFTH QUARTERLY REPORT

for the period 1 October to 31 December 1980

C.R. DICKSON, W.FELDER, AND R.K. GOULD

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Approved by

Hartwell F. Calcote
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Princeton, New Jersey

FOREWORD AND ACKNOWLEDGMENTS

During this report period Dr. J. Allen and A. Wilczynski contributed to this program.

ABSTRACT

The objective of this phase of the program is to characterize the kinetics and mechanism of the formation and growth of silicon particles from the decomposition of silane at high temperatures. The experiments are aimed at determining the rates at which gas-phase species form silicon particle precursors, the time required for silane decomposition to produce silicon particles, and the competing rate of growth of silicon seed particles injected into a decomposing silane environment.

In this reporting period, the AeroChem high-temperature fast-flow reactor (HTFFR), modified to study the decomposition of silane and the subsequent growth of particles, was tested and particle growth measurements were made as functions of temperature (600-1200°C), pressure (50-550 Torr), and residence time (0.5 to 30 ms). Optical diagnostics consisting of attenuation and 90° Mie scattering of the light from He-Ne or Ar⁺ lasers were used to determine the appearance growth rates and absolute sizes of the particles. The extent of silane decomposition was measured by infrared absorption spectroscopy. Particles were collected in the HTFFR observation zone as a check on the particle concentrations measured optically. Scanning electron micrographs (SEM) of the collected particles confirmed the optical size measurements.

Representative data obtained at 900°C indicate that: (1) Particles formed from silane decomposition are spherical in shape and have a narrow size distribution at a given time in the decomposition/growth process. (2) Silane disappearance and particle growth are controlled by heterogeneous gas-particle interactions for particles greater than 0.05 μm radius. (3) Tentatively, particles larger than 0.05 μm radius have a cellular structure (from SEM of collected particles). These results led to the formation of a simplistic model for the particle growth process.

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I. INTRODUCTION

The thermal decomposition of silane is one of the processes currently being considered by JPL as a source of low cost solar grade silicon for photovoltaics. The objective of this work at AeroChem is to provide data to support production process development by characterizing the kinetics and mechanism of the formation and growth of silicon particles from the decomposition of silane at process temperatures. The experiments are aimed at determining the rates at which gas-phase species form silicon particle precursors, the time required for silane decomposition to produce silicon particles, and the competing rate of growth of silicon seed particles injected into a decomposing silane environment.

The effort on this contract comprises:

1. Construction of a high-temperature fast-flow reactor (HTFFR) and assembly of diagnostic equipment appropriate for studying the rate of decomposition of SiH_4 and the rate of formation and growth of Si particles.
2. Particle formation studies to determine the time required for SiH_4 decomposition to proceed to the stage where Si particle formation occurs.
3. Particle growth studies to determine the rate of growth of silicon seed particles injected into a decomposing SiH_4 environment.
4. Decomposition studies to determine the rate at which gas-phase species react to form Si particle precursors.
5. Data interpretation to apply to the performance of processes for producing Si from SiH_4 .

Part 1 was completed on schedule and reported in the fourth quarterly report on this contract.¹ In this reporting period, essentially all of the experimental data were collected for parts 2 and 3, preliminary work on part 4 was begun, and the analysis of the data for part 5 is underway. The large amount of data collected has not all been analyzed and drafted at the writing of this report. Thus, only representative data will be presented here to show how the resulting conclusions were made. Full presentation of the data will be made in the final report.

In this report we will present the light scattering results, particle growth rate studies, particle collection studies, particle concentration studies, and a preliminary model to explain the experimental results.

II. TECHNICAL DISCUSSION

A. LIGHT SCATTERING RESULTS

The Mie theory is a formal solution of Maxwell's equations for the scattering of electromagnetic radiation by spherical homogeneous particles of arbitrary size. The theory is fully explained in several references,²⁻³ hence, only the relevant expressions will be presented here. The results for the scattering and extinction cross sections are

$$C_{\text{scatt}} = \frac{\lambda^2}{2\pi} \sum_{n=1}^{\infty} (2n+1) \left(|a_n|^2 + |b_n|^2 \right) \quad (1)$$

$$C_{\text{ext}} = \frac{\lambda^2}{2\pi} \sum_{n=1}^{\infty} (2n+1) \operatorname{Re}(a_n + b_n) \quad (2)$$

for the light of wavelength λ incident on a sphere of radius r . The Mie coefficients a_n and b_n are complicated expressions involving spherical Bessel functions and their derivatives and are functions of the complex index of refraction m and the size parameter $x = 2\pi r/\lambda$.

For convenience, the cross sections C_{ext} and C_{scatt} are often expressed as the efficiencies Q_{ext} and Q_{scatt} defined as the ratio of the Mie cross section to the geometrical cross section (πr^2), i.e.,

$$Q_{\text{ext}} = \frac{C_{\text{ext}}}{\pi r^2} \quad (3)$$

and

$$Q_{\text{scatt}} = \frac{C_{\text{scatt}}}{\pi r^2} \quad (4)$$

When these efficiencies are plotted as a function of the particle size parameter they often exhibit an oscillatory behavior which converges to a value of 2. The oscillatory behavior is attributed to light interference or diffraction effects which are observed in the far field. The convergence to a value of 2 is due both to light being removed geometrically (the particle shadow) and to light being removed by interference or diffraction effects.

The Mie oscillations are distinct functions of the particle size and they thus form the basis for determining particle size. They were used by Vietti and Schuster⁴ to determine the sizes of water droplets formed in cloud chamber experiments. Experimentally, they obtained Mie oscillations in the scattered light intensity as a function of time as the water droplets increased in size. Since each peak or valley in the scattered light intensity was characteristic of a particle size, the particle size as a function of time was determined.

We anticipated the observation of Mie oscillations in both the light extinction and light scattering data obtained with our HTFFR apparatus. Increasing the residence time of the silane gas in contact with the hot zone of the HTFFR (by varying the position of the cooled silane inlet) was expected to increase the size of the silicon particles produced from the thermal decomposition of silane. Unlike the cloud chamber experiments the flow tube method used here establishes an independent time base due to the flow itself. Thus we could hold the particles in the observation zone in a steady-state fashion to perform experimental diagnostics on a preselected particle size.

During the initial experiments several important results were obtained. The observation of distinct Mie oscillations in both the extinction and scattering data indicated that particles formed from the gas phase had grown to radii greater than $\approx 0.1 \mu\text{m}$. This conclusion was also supported by the simultaneous observation that the scattered laser light at 90° was depolarized.

Representative extinction data are plotted in Fig. 1 as a function of residence time, showing the distinctive Mie oscillations. These results were obtained at 900°C , an argon bath pressure of 200 Torr, and a SiH_4 flow rate of $2.5 \times 10^{-5} \text{ mol s}^{-1}$. The y-axis of this plot is proportional to the efficiency Q_{ext} as defined by Eq. (3). The x-axis of the plot is the residence time in the HTFFR (distance/velocity). The positional dependence of the oscillations shows directly the steady-state nature of the experiments and demonstrates that the x-axis is also proportional to the particle size. For the conditions of Fig. 1, the time required to observe the first peak of the Mie oscillations is $\approx 2.5 \text{ ms}$. The appearance of additional peaks indicates that the particles continue to grow for $\approx 20 \text{ ms}$.

Another observation of great importance is that results like those shown in Fig. 1 demonstrate that the particles formed have a monodisperse size distribution. This is generally assumed to be the case when Mie oscillations are observed in light extinction and scattering data. Vietti and Schuster⁴

FIGURE 1 MIE RESONANCE PEAKS IN RAW EXTINCTION DATA

showed that the sharpness of the peaks is directly related to the standard deviation of the normal distribution of sizes which was assumed in their work. When the standard deviation had a value of 2, the Mie oscillations disappeared. Thus, the Mie oscillations shown in our work could be compared with computer calculations to determine the exact size distribution of the particles produced.

Other preliminary conclusions and speculations can be drawn from the initial data. It seems likely that the observed particle growth (from $r \approx 0.05 \mu\text{m}$ upward) results from gas-particle interactions rather than agglomeration of small particles because silicon is solid at 900°C and because agglomeration would be expected to be "slow" under the present conditions. Growth of particles prior to the appearance of the Mie oscillations (in the case of Fig. 1, before 2.5 ms) could probably also be observed using Rayleigh scattering methods (which are beyond the scope and funding of the present work). It is likely that much of the particle growth in these early stages is the result of homogeneous processes and we therefore preliminarily conclude that the time domain for the observation of the homogeneous and heterogeneous particle growth kinetics can be defined.

Because the Mie oscillations observed in the scattering and extinction data are used to determine the size of the particles, their nature was examined in detail. Several peaks were not observed (missed) when the cooled inlet was moved in 1.0 cm increments. Detailed ripple structure was found when the cooled inlet was moved in 0.1 cm increments. All of the Mie oscillations, but not the ripple structure, were observed when the cooled inlet was moved in 0.5 cm increments. Thus, the degree of structural detail in the oscillations which is measured can be regulated by controlling the increments in which the position of the cooled inlet is changed. Figure 2 illustrates this for extinction data. To confirm that the detailed structure was not an artifact, computer calculations using the Mie code were made. The dotted line shown in Fig. 3 is the predicted Mie oscillation while the solid line is the detailed ripple structure also predicted by using a finer calculational risk. Thus, the observed ripple structure is predicted by theory and the experimental observation is assumed to be real. Fortunately, this complex structural detail is not needed for determining particle size.

The detailed considerations of the Mie oscillations thus established that the positions of the gross features were directly related to particle radii. Computer calculations using Mie scattering theory were then made for the He-Ne laser wavelength of 632.8 nm, a refractive index of $m = 3.44 - 0.02i$, and a particle number density of 10^8 particles cm^{-3} . A delta function was used to simulate a monodisperse particle size distribution. The quantities calculated were the extinction and the scattering efficiencies and the differential scattering cross section as a function of angle (to obtain the scattered light intensity at 90° as a function of particle radius). Figure 4 shows the results for the relative scattered light intensity at 90° as a function of radius; the first peak occurs at $r \approx 0.2 \mu\text{m}$. The peak of the sixth Mie oscillation occurs at $r \approx 0.95 \mu\text{m}$. Thus, based on this calculation, the positions of the Mie oscillations obtained as a function of residence time in the HTFFR apparatus are now calibrated for various silicon particle sizes. This is shown in Fig. 5 for 90° scattering data obtained at 200 Torr, 900°C , a SiH_4 flow rate of $4.5 \times 10^{-5} \text{ mol s}^{-1}$, and a buffer gas velocity of 500 cm s^{-1} . Directly measured particle sizes obtained from SEM of silicon samples collected at various cooled inlet positions agree with the above calculations to within a few percent. This confirmation makes it possible to be confident that simply counting the observed Mie oscillations and comparing them with the calculated curves (e.g., Fig. 4) is a valid means for determining the particle sizes.

FIGURE 2 INCREASE IN THE STRUCTURE OF THE MIE OSCILLATIONS IN EXTINCTION DATA AS THE POSITION INCREMENTS OF THE COOLED INLET ARE DECREASED

FIGURE 3 RESULTS OF MIE THEORY CALCULATIONS WHICH SHOW THE RIPPLE STRUCTURE (SOLID LINE) IN THE MIE OSCILLATIONS (DOTTED LINE)

FIGURE 4 CALCULATED SCATTERED LIGHT INTENSITY AT 90° USING MIE THEORY

FIGURE 5 EXPERIMENTAL SCATTERED LIGHT INTENSITY AT 90° OBTAINED AT $P = 200$ TORR, $T = 900^\circ\text{C}$, AND $v = 500 \text{ cm s}^{-1}$

The behavior of the Mie oscillations was also investigated in the region where the extinction efficiency approaches a value of 2. This occurs in the size region where the circumference of the particle is ≈ 10 times the probing wavelength. For 632.8 nm , this corresponds to a particle radius of $1.0 \mu\text{m}$. For small attenuation the attenuated light intensity has a quadratic dependence on the particle radius (see Appendix A for a derivation):

$$I/I_0 = 1 - (2\pi n\ell)r^2 \quad (5)$$

where n is the particle number density and ℓ is the optical path length. Preliminary investigation of the extinction data for particle radii greater than $1 \mu\text{m}$ showed no obvious quadratic dependence of the attenuated light intensity on particle size. The implication of this result is that the particle number density is decreasing with increasing residence time in the HTFFR flow tube. Qualitatively, this conclusion is reinforced by the apparent decrease in both extinction and scattering intensities (cf. Fig. 5--the intensity is dependent upon n) with increasing residence time.

The conclusions about the growth of silicon particles produced by the thermal decomposition of silane are:

1. An initial growth of the particles occurs in an induction period of approximately 1 to 2 ms at 900°C producing particles less than 0.05 μm radius.
2. The bulk of particle growth occurs in 1-20 ms after the induction period. The particles grow to $\approx 1 \mu\text{m}$ or larger in this period at a temperature of 900°C.
3. The calibration of the Mie oscillations by Mie theory calculations agreed well with the determination of particle size by SEM.
4. The sharpness of the peaks in the Mie oscillations means that the particles have a highly monodisperse size distribution.
5. The decrease in both extinction and scattering intensities with residence time, and the lack of a quadratic dependence in the large particle radius attenuation data suggest a decrease in the particle concentrations with increasing residence time.

B. PARTICLE GROWTH RATES

Light scattering data such as those shown in Fig. 5 have been obtained for total pressures of 120, 200, and 350 Torr and at temperatures of 600, 900, and 1200°C. These data were obtained using light from the 632.8 nm He-Ne and the 514.5 nm Ar^+ laser lines. Particle sizes were extracted by comparison with the computer calculations. Figure 6 shows an example of this kind of information. In it, the growth of the particle radii is plotted as a function of residence time for a pressure of 200 Torr, a temperature of 900°C, and a bath gas velocity of 500 cm s^{-1} . The growth rate decreases with increasing residence time both because silane is being depleted and because its mass deposition rate (proportional to r^3) is increasing.

Another experiment which provides information about particle growth rates is to vary the silane concentration. The relative intensity of scattered light was plotted as a function of silane concentration (varied over a factor of 10) as shown in Fig. 7. This experiment was performed at 900°C and 200 Torr by following the growth of particular resonance peaks. The silane pressure in psig is the pressure behind a calibrated orifice and is related directly to the concentration of silane entering the hot HTFFR tube. These plots will be reduced to concentrations for the final report. The conditions

FIGURE 6 RATE OF GROWTH OF SILICON PARTICLES
AT 900°C AND 200 TORR

FIGURE 7 PLOT OF RELATIVE SCATTERED LIGHT INTENSITY
AT 90° AS A FUNCTION OF SILANE CONCENTRATION FOR PARTICLES
OF $r \approx 1.0 \mu\text{m}$

of Fig. 7 produced particles slightly larger than $1.0\text{ }\mu\text{m}$. It is observed that there is a limiting value for the concentration of this particle size since the intensity is proportional to the particle concentration for a constant particle size. The intensities of the Mie oscillations for two other particle sizes are plotted in Fig. 8 as a function of the silane concentration; it can be seen that increasing the silane concentration increases the number density of larger particles but not of the smaller ones. Thus it appears that increasing the silane concentration will increase the concentration of larger particles to a limiting value. It should be noted that the rate of particle growth did not significantly change with an increase in silane concentration.

The tentative conclusions from this work are as follows:

1. Increasing the temperature from 600-1200°C at given bath gas pressures increases the particle growth rate.
2. Increasing the bath gas pressure at a constant temperature apparently increases the particle growth rate at 900°C while the reverse appears true at 1200°C.
3. Increasing the initial silane concentration at a given pressure and temperature does not affect the particle growth rate.

Fuller analyses of these data are now in progress and will be presented in the final report.

C. PARTICLE COLLECTION STUDIES

Particles produced by the thermal decomposition of silane in the HTFFR tube were collected in the observation zone for:

1. Scanning electron micrographs, to provide a verification of the Mie theory calculations used to calibrate the particle sizes determined from the light scattering data.
2. Some information on the morphology of the particles produced by the thermal decomposition of silane under controlled reaction conditions.
3. A semiquantitative estimate of particle concentration.

The silicon particles were collected at a bath gas pressure of 200 Torr, gas velocity of 500 cm s^{-1} , and temperatures of 600, 900, and 1200°C, for various silane residence times in the HTFFR tube.

FIGURE 8 PLOT OF INTENSITY OF TWO DIFFERENT MIE OSCILLATION PEAKS CORRESPONDING TO TWO DIFFERENT PARTICLE RADII AS A FUNCTION OF SILANE CONCENTRATION

Experimentally, a 1/4 in. diam stainless steel tube was placed in the observation zone through one of the observation ports of the HTFFR apparatus (see Fig. 9) and some of the particle-laden gas stream was withdrawn through an external paper filter on which particles collected. Although it is perfectly adequate to provide samples for SEM sizing and morphology analysis this configuration is not ideal for particle concentration measurements. For more than the semiquantitative information desired here, a sampling cone designed to collect particles in the observation zone without disturbing the streamline flow of the gas is needed.

The SEMs (see Figs. 10 and 11) of the particles collected at residence times of 3 ms and 16 ms for the conditions of 200 Torr and 900°C revealed that the particles were spherical in shape and monodisperse in size distributions, highly consistent with the light scattering observations. The radii of the particles from SEM ($\approx 0.25 \mu\text{m}$ at 3 ms and $\approx 0.9 \mu\text{m}$ at 16 ms) were in good agreement with results obtained from the light scattering measurements. The most interesting feature is that both the samples appear to consist of many smaller particles having radii $\approx 0.05 \mu\text{m}$. This observation, combined with the light scattering results, suggests an empirical model to explain both the homogeneous

FIGURE 9 COLLECTION OF PARTICLES PRODUCED BY
THE THERMAL DECOMPOSITION OF SILANE

and heterogeneous particle growth kinetics. This will be presented in the last section of this report.

D. PARTICLE CONCENTRATION STUDIES

The particle concentrations produced by the thermal decomposition of silane are determined as a function of time from the measured particle sizes combined with a measurement of the fraction of silane decomposed. The collection studies provide a semiquantitative check on the primary measurement.* Both methods assume that the particles are silicon. If the particles were $(\text{SiH}_2)_n$ polymers, a seven percent error would be introduced. However, the

* Preliminary data and a brief discussion of these methods have been previously presented.⁷ In this section, we will describe the analysis in more detail. A large number of measurements have been carried out, but experimental limitations in measuring the fraction of SiH_4 decomposed over the full range of residence times prevent our reducing and presenting them here. Measurements are now in progress to correct this problem, after which the data now in hand can be completely reduced.

FIGURE 10 SEM OF SILICON PARTICLES THAT ARE $\approx 0.25 \mu\text{m}$ IN RADIUS

FIGURE 11 SEM OF SILICON PARTICLES THAT ARE $\approx 0.9 \mu\text{m}$ IN RADIUS

stoichiometry is probably something between pure Si and $(\text{SiH}_2)_n$ polymers, making this error considerably less. Both methods are also based on the assumption that a sphere of radius R is composed of smaller spheres of radius r ($= 0.05 \mu\text{m}$) considered to be in a close packing geometry.

The number of silicon atoms in a silicon sphere of radius r is given by

$$N_{\text{Si}}(r) = \frac{4/3\pi r^3}{V_{\text{Si}}} = \frac{4/3\pi r^3}{M/\rho N} \quad (6)$$

where V_{Si} is the volume of a silicon atom calculated from the density of silicon (ρ), Avogadro's number (N), and the molecular weight of Si ($M = 28 \text{ g mol}^{-1}$). The number of radius r spheres contained in a larger sphere of radius R is given by

$$N_r(R) = ((4/3\pi R^3)/(4/3\pi r^3)) \cdot 0.74 \quad (7)$$

The factor 0.74 accounts for hexagonal close packing of the smaller spheres. Thus, the number of silicon atoms in the spheres of radius R is

$$N_{\text{Si}}(R) = N_r(R) \cdot N_{\text{Si}}(r) = 0.74 \cdot (4/3\pi R^3) \cdot (\rho N/M) \quad (8)$$

To obtain the particle concentration, $n(R)$ from the fraction of SiH_4 decomposed (method 1) the following mass balance expression is used:

$$n(R) = \frac{[\text{SiH}_4]_0 f}{N_{\text{Si}}(R)} \quad (9)$$

where f is the fraction of silane decomposed and $[\text{SiH}_4]_0$ is the initial silane concentration. The numerator represents the total number of silicon atoms available from the decomposition of silane and the denominator represents the number of atoms in a silicon sphere of radius R which is composed of smaller spheres of radius r .

To obtain the particle concentration by collection (method 2) the following expression is used:

$$n = n_{\text{atoms}}/N_{\text{Si}}(R) \quad (10)$$

Equation (8) gives a value for $N_{\text{Si}}(R)$ and n_{atoms} , the number of silicon atoms collected, is given by:

$$n_{\text{atoms}} = \left(\frac{w}{\Delta t} \right) \left(\frac{N}{M} \right) \cdot \frac{1}{v_a} \quad (11)$$

where w is the mass collected in the time Δt , from a flow of velocity v impinging on a collecting tube of cross section area a ($\approx 0.32 \text{ cm}^2$ in these experiments).

Results obtained using the collection method are displayed in Table I for the conditions $[\text{SiH}_4]_0 = 1 \times 10^{16} \text{ cm}^{-3}$, $P = 200 \text{ Torr}$, $v = 500 \text{ cm s}^{-1}$.

TABLE I
PARTICLE CONCENTRATION IN HTFFR MEASURED BY COLLECTION

T ($^{\circ}\text{C}$)	Residence Time (ms)	Particle Radius (μm)	$n(R)$ (cm^{-3})
600	6	0.52	1.1×10^3
900	3	0.25	2.7×10^5
	16	1.00	$(2.7-3.3) \times 10^4$
	22	1.27	2.8×10^4
1200	6	0.60	9.9×10^3

A much more complete set of data on silane decomposition has been obtained as a function of residence time for the pressures of 120, 200, and 350 Torr at temperatures of 600, 900, and 1200 $^{\circ}\text{C}$. Reduction of this data by method 1 will be performed when the complete set of SiH_4 decomposition data is obtained. Preliminarily, these data appear to support the decrease in n at early times, although this is not certain. Such a decrease might be explained as wall loss or agglomeration, although rates of these processes calculated using any physically reasonable parameters appear to be too small to account for differences as large as suggested.

E. PRELIMINARY MODEL

The scanning electron micrographs obtained on the collected particles indicated a cellular structure where the larger spheres were composed of many smaller $0.05 \mu\text{m}$ spheres. This observation, combined with the present experimental results, suggests a speculative model comprising both the homogeneous and heterogeneous particle growth kinetics.

Initial growth of the silicon particles begins with the homogeneous nucleation of Si atoms or SiH_2 molecules resulting from the thermal decomposition of silane. The particles continue to grow as spheres until they reach radii of approximately $0.05 \mu\text{m}$. The mechanism of growth for these small spheres

probably includes agglomeration as suggested by Bauer and coworkers⁵ and by Levin.⁶ This growth is limited by a currently unknown mechanism which may be related to conditions that terminate the polymerization of SiH_2 species. This is the basis of the homogeneous particle growth process and the present results indicate that this growth is fast (< 1 ms).

The continued growth of the small particles is then described by heterogeneous processes which require several milliseconds for the spheres to grow to radii of $\approx 1.0 \mu\text{m}$. The growth seems to result from the formation of many additional small spheres growing at the surface of the initial "seed" sphere. The rate at which the smaller spheres form at the surface of the larger sphere must be greater than the rate at which silane decomposition products form the seed spheres. Otherwise, many new seed spheres would result as the large spheres grow, resulting in a polydisperse size distribution (the optical and SEM measurements indicate highly monodisperse particle size distributions) unless coagulation is much more rapid than physically reasonable. Nearly 100 small ($0.05 \mu\text{m}$ radius) spheres are required to form a larger sphere $0.25 \mu\text{m}$ in radius (assuming hexagonal close packing of the spheres), and 4300 small spheres are required for a particle having a radius of $0.9 \mu\text{m}$. In principle, this growth can continue indefinitely provided sufficient SiH_4 is present. Thus, the homogeneous process is described by a rapid growth of one sphere and the heterogeneous process is described by a slower growth of many small spheres from the surface of the "seed" sphere as depicted in Fig. 12.

III. PLANS

During the next reporting period, additional experimental work on establishing SiH_4 decomposition data and seeded particle growth rates will be carried out. Measurements on atomic and molecular species will also be performed. The ongoing data interpretation/utilization effort will be continued.

IV. NEW TECHNOLOGY

No reportable items of new technology were identified in this quarter.

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FIGURE 12 SCHEMATIC DRAWING REPRESENTING THE GROWTH OF SILICON PARTICLES PRODUCED BY THE THERMAL DECOMPOSITION OF SILANE

V. REFERENCES

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APPENDIX A

The extinction of light is given by

$$\frac{I}{I_0} = e^{-\tau \ell} = e^{-(n \ell C_{\text{ext}})} \quad (\text{A1})$$

where τ is the turbidity, ℓ is the light path length, C_{ext} is the extinction cross section, and n is the concentration of particles contained in the volume intercepted by the light beam. For small attenuation, i.e., $I/I_0 \approx 0.9$, it is possible to expand the exponential to obtain

$$\frac{I}{I_0} = 1 - (n \ell C_{\text{ext}}) \quad (\text{A2})$$

In the region where the circumference of the particle is ≈ 10 times the probing wavelength (632.8 nm), the efficiency factor approaches a value of 2, i.e.,

$$Q_{\text{ext}} = \frac{C_{\text{ext}}}{\pi r^2} \approx 2 \quad (\text{A3})$$

or

$$C_{\text{ext}} = 2\pi r^2$$

substituting into Eq. (A2)

$$\frac{I}{I_0} = 1 - (2\pi n \ell) r^2 \quad (\text{A4})$$

Thus, the attenuated light intensity exiting from a volume of particles which scatters and absorbs light will show a quadratic dependence on r in the region where $2\pi r/\lambda$ approaches 10.