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## Dynamics of spontaneous roughening on the GaAs(001)-(2×4) surface

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### Abstract

The dynamics of a random distribution of spontaneously formed 2D GaAs islands are studied using scanning tunneling microscopy. The equilibrium concentration of islands is easily tuned from 0% to 50% coverage by only changing the As<sub>4</sub> overpressure. Images taken during the early stages of island formation reveal the roughening transition primarily occurs through an intermediate pit formation phase. Interestingly, pit formation in the middle of an otherwise pristine terrace is overwhelmingly preferred to atom detachment from the edges of the terraces.

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### 1. Introduction

The phenomenal growth in wireless communications and optoelectronics technology is making zinc-blende III–V semiconductor substrates an increasingly important component of the semiconductor industry (see for example, [1]). Naturally, there is an extensive effort to develop both higher performance devices as well as novel multifunctional devices, all of which require stricter control over the growth process. To achieve this, a deeper understanding of the fundamental processes involved in making device structures, such

as attachment–detachment rates, diffusion and nucleation is required.

Macroscopic measurements of gallium adatom diffusion using kinetic studies has dominated the research community. For example, monitoring growth under a shadow mask, has been used to estimate the Ga diffusion length [2]. In addition, the decay of intensity oscillations in reflection high-energy electron diffraction (RHEED) with increasing temperature has been used extensively to study diffusion of Ga on GaAs [3–5]. Surface diffusion studies for the III–V compound semiconductors are necessarily complicated since these are binary compounds.

Recently, many studies on the GaAs(001) surface have documented the phenomenon of spontaneous formation of GaAs islands [6–10]. These studies show that by simply altering the As<sub>4</sub>

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## REPORTS

### Spatially Resolved Spin-Injection Probability for Gallium Arsenide

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We report a large spin-polarized current injection from a ferromagnetic metal into a nonferromagnetic semiconductor, at a temperature of 100 Kelvin. The modification of the spin-injection process by a nanoscale step edge was observed. On flat gallium arsenide [GaAs(110)] terraces, the injection efficiency was 92%, whereas in a 10-nanometer-wide region around a  $\bar{1}$ [11]-oriented step the injection efficiency is reduced by a factor of 6. Alternatively, the spin-relaxation lifetime was reduced by a factor of 12. This reduction is associated with the metallic nature of the step edge. This study advances the realization of using both the charge and spin of the electron in future semiconductor devices.

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The ability to exploit the spin of the electron in semiconductor devices has the potential to revolutionize the electronics industry (1-3). The realization of "spintronic" devices is growing nearer as sources for spin-polarized electrons have become available in both ferromagnetic metals and ferromagnetic semiconductors (4, 5). In addition, polarized electrons can move up to 100  $\mu\text{m}$  in gallium arsenide (GaAs) without losing their polarization, so that coherent transport through the active region of a device structure is feasible (6). However, one of the most difficult challenges in creating "spintronic" devices is the ability to transfer the polarized electrons from a ferromagnetic material into a

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## RELAXATION PHENOMENA AND THERMODYNAMICS OF LIQUIDS AT VERY HIGH PRESSURES

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### ABSTRACT

Complex liquid glass-forming systems ranging from those composed of simple molecules to polymer melts and amorphous polymers have been studied extensively as a function of temperature resulting in a basic understanding of liquid-state dynamics and glass transition phenomenology as these systems are supercooled to the vitreous state. An important aspect of this problem that remains largely unexplored, and that is relevant to the topic of this symposium, involves liquid-state dynamics and vitrification (as well as crystallization) in the regime of high pressure and high density. We describe work on "fragile" to "intermediate strength" simple organic glass-forming liquids where both temperature (T) and pressure (P) are varied. Diamond anvil cells are used to achieve pressures exceeding 10 GPa. Several optical and light scattering techniques are used to explore both static and dynamic properties of these systems. High-pressure Brillouin scattering enables us to model the longitudinal relaxation time in these systems as well as their equations of state. These can now be refined by direct measurements of the pressure dependence of the glass transition,  $T_g(P)$ . Finally, we summarize depolarized light scattering studies which allow us to compare both the isobaric and isothermal evolution of structural ( $\alpha$ ) and fast ( $\beta$ ) relaxation processes.

### INTRODUCTION

An increasing effort has been directed in recent years at understanding the physical and chemical properties of materials under extreme conditions of very high pressure. This effort has many driving forces including basic curiosity, the dearth of pressure-dependent data relative to other variables such as temperature or composition, the fact that many material phases naturally exist or are formed under extreme pressures, and technological need. For the case of liquids, an example of the last of these is elastohydrodynamic lubrication, a lubrication regime where both hydrodynamic action and deformations of the contact surfaces must be considered. Lubricant pressures can reach values as high as several tens of kilobars at Hertzian contact points (or lines) in various types of gears, cams, or bearings.<sup>1</sup> In this paper we describe our work aimed at exploring both thermodynamic and dynamical properties of several organic liquids in the regime of very high pressures and hence very high density.

Given the relative ease of conducting temperature-dependent experiments, i.e., of achieving and controlling a specific temperature, it is generally true that temperature-dependent properties of most condensed matter systems are understood much better than pressure-dependent properties are. During the past two decades this situation has begun to change as high-pressure technology has evolved significantly, due largely to the development of diamond anvil cells (DACs)<sup>2</sup> and the ruby fluorescence manometer.<sup>3</sup> This has opened the way for the exploration of vastly greater regions of

## Pressure and Temperature Dependence of Glass-Transition Dynamics in a "Fragile" Glass Former

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A depolarized light-scattering study of isopropylbenzene has been carried out at pressures from 1 bar to 7.6 kbar and at temperatures from 293 to 122 K. Both the supercooled and superpressed liquids show two-step relaxation processes. The faster relaxation in both cases can be described by a mode-coupling  $\beta$  relaxation theory. Comparison of the pressure and temperature data indicate that density is not the only relevant parameter required to explain the evolution of the  $\beta$  relaxation dynamics as the liquid-glass transition is approached.

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For many glass-forming materials, a liquid-glass transition can be induced either by decreasing the temperature through a glass-transition temperature  $T_g$  or by increasing the pressure through a glass-transition pressure  $P_g$ . In the latter class of experiments, relaxation rates were first obtained by Bridgman [1] who measured the viscosity of several liquids up to 30 kbar. Later, viscosity measurements were extended to higher pressures through the use of multianvil presses and diamond anvil cells (DAC's) [2]. Dynamical information has also been obtained in liquid-glass-forming systems up to 90 kbar in the frequency range 0.1 to 450 kHz via dielectric relaxation [3], and at frequencies as high as 150 MHz in the pressure regime  $P < 5$  kbar by ultrasonic absorption [4]. Light-scattering techniques in the DAC have been used much more recently to measure high-pressure relaxation times in the GHz regime up to 120 kbar [5]. However, the great majority of studies of liquid-glass dynamics have been performed with isobaric temperature scans due to the relative difficulty of high-pressure measurements. In particular, no pressure-scan experiment has heretofore been reported in the frequency range required to test the mode-coupling theory (MCT), which predicts a fast  $\beta$  relaxation regime [6] located between the low-frequency  $\alpha$  relaxation and the high-frequency microscopic excitation band.

For the temperature-induced liquid-glass transition, several neutron scattering [7] and depolarized light scattering [8] measurements of some fragile glass-forming materials observed the two-step relaxation process in the supercooled liquid near the liquid-glass transition. The fast relaxation processes are found to follow the scaling law predictions of the MCT  $\beta$  relaxation process. It is of critical interest to determine whether the evolution of  $\beta$  relaxation dynamics with varying temperature and varying pressure follow a similar pattern, and whether the MCT can be applied for both cases. For temperature- and pressure-induced glass-transition processes, the density

changes via thermal expansion and compressibility, respectively. Therefore, an important question is whether density is the dominant parameter for the liquid-glass transition dynamics or if thermal effects also play an important role. A deeper understanding of the liquid-glass transition requires information on the role played by both parameters.

To address these questions, we have carried out a wide-frequency-range depolarized-light-scattering study of isopropylbenzene (cumene)  $[\text{C}_6\text{H}_5\text{CH}(\text{CH}_3)_2]$ ,  $T_m = 177$  K,  $T_g \approx 125$  K] with varying pressure at  $T = 293$  K (isothermal process) and with varying temperature at  $P = 1$  bar (isobaric process). Cumene is a simple molecular system. At ambient pressure, it is a "fragile" glass-forming material on an Angel plot of the temperature-dependent viscosity  $\eta(T)$  [9]. We have measured the  $T = 293$  K pressure dependence of the viscosity  $\eta(P)$  up to 14 kbar. Extrapolation to  $\eta(P) \approx 10^{13}$  P of this data through a Tait fit for the pressure-dependent density [1] and a free-volume fit [10] for the density-dependent viscosity yields  $P_g \approx 25$  kbar ( $\rho_g \approx 1.224$  g/cm<sup>3</sup>). It is also a fragile glass former on an extended Angel plot [11] of the pressure-dependent viscosity.

Depolarized light-scattering measurements were performed in a near-back-scattering ( $\theta = 173^\circ$ ) geometry. The experimental procedure, the Sandercock tandem Fabry-Pérot interferometer, and the Raman apparatus have been described previously [8]. The cumene sample (99%) was obtained from Alfa products. In the variable pressure measurement (VPM), a Merrill-Bassett-type DAC was used. Standard ruby fluorescence techniques were used to measure the pressure in the sample, which was used as supplied by the manufacturer. A complete set of spectra with different free spectral ranges was collected at each pressure before the sample pressure was changed. Because of pressure-induced birefringence in the diamond, leakage of the longitudinal acoustic (LA)