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Laser–plasma simulations of astrophysical phenomena and novel applications to semiconductor annealing

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Abstract

At the frontier of plasma physics and technology are applications of laser-generated plasmas to laboratory simulations of astrophysical phenomena and to industrial processing. This article presents work at the Naval Research Laboratory in both of these areas. We show how laser plasmas are used to measure a blast wave corrugation overstability important in astrophysics. Detailed atomic physics calculations of radiative cooling within the blast front are used to develop a criterion of the existence of the overstability and are used to explain the experimental results. The criterion depends on quantities such as element abundances, densities, temperatures, and blast wave velocities—quantities which can be measured spectroscopically—and therefore used to infer whether astrophysical blast wave nonuniformities are the result of this instability. In other experiments, high-velocity jets are formed in the laboratory using miniature hollow cones. Jets produced by these cones are used to study the physics of jets occurring in supernovae and in star-forming accretion disks. In industrial semiconductor processing, annealing, that is, removing crystal damage and electrically activating the semiconductor, is a critical step. Industrial annealing techniques most often utilize heat generated by an oven, flash lamps, or a low-power laser. During such heating dopants within the semiconductor lattice diffuse and spread. This degrades the performance of circuits in which the individual circuit elements are very close to each other. We are developing an annealing technique in which shock or sound waves generated by a laser plasma are used to anneal the semiconductor. We have demonstrated that the method works over small areas and that it does not lead to significant dopant diffusion.

Keywords: Athermal; Annealing; Blast-wave; Instability; Supernovae

1. INTRODUCTION

Despite orders-of-magnitude discrepancies in spatial and temporal scales, laser-produced plasmas created in the laboratory can be used to model and study astrophysical phenomena that are not otherwise readily accessible. That this is so was first suggested in a 1964 paper by J.M. Dawson (Dawson, 1964) and the first experimental results were published shortly thereafter (Tsuchimori *et al.*, 1968; Zakharov *et al.*, 1986; Grun *et al.*, 1991). Among the first experiments performed was one in which a corrugation overstability predicted (Vishniac, 1983; Ryu & Vishniac, 1987; Vishniac & Ryu, 1989) to occur in radiative supernovae blast waves was observed (Grun *et al.*, 1991) and studied in the laboratory using laser-produced plasmas. These authors produced blast waves in various more radiative and less radiative gases, and showed that blast waves in the more radiative gas rippled with a power-law growth rate close to theoretical predictions, whereas blast waves in less radiative gas remained stable. The relevance of these laboratory experiments to astrophysics was discussed by MacLow and Norman (1993). Explaining these observations requires detailed calculations of the radiative cooling of the blast front in order to understand how radiative a radiative blast wave must be to be overstable. By performing such calculations we found that in these laboratory experiments, the blast front must cool significantly during a distance on the order of the ion mean free path. Criteria for the existence of the instability in the laboratory or in space were developed and found to

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depend on element abundances, densities, temperatures, and blast wave velocities, quantities that can be measured in outer space (Laming & Grun, 2002, 2003). The criterion and the formalism developed can, therefore, be helpful in astrophysical situations.

Another area in which laser-produced plasmas can simulate astrophysical phenomena is the propagation and interaction with matter of dense, high-velocity cumulative jets (Manka *et al.*, 1989). Such jets can be used to examine theories that involve jets in the causation of supernovae explosions and in star accretion disks (Khokhlov *et al.*, 1999). Jets can also be used to study phenomena such as shock loading, generation of high-atomic-number long-scale-length plasmas, radiative hydrodynamics of dynamically mixed gases, and opacity of high-atomic-number plasmas, and can be used as efficient sources of high energy X rays (Back *et al.*, 2001)

Laser-generated plasmas also have a role at the other extreme of spatial and temporal dimensions, that is, very short and fast spatial and temporal time scales. They may, in fact, become an enabling technology in a critical process in the industrial production of semiconductors called "annealing" (Donnelly *et al.*, 1997, 2001; Grun *et al.*, 1997, 1998*a*, 2000*a*; Rao *et al.*, 2003). During this step, structural damage caused by the insertion of dopants into a crystal that is to become the semiconductor is removed. Annealing also relocates the dopants, which have been inserted at random locations within the crystal lattice, to locations where they are electrically active and cause the crystal, heretofore highly resistive, to become a semiconductor. Conventional semiconductor annealing methods utilize heat generated by an oven, flash lamps, or by a low power laser. These heating techniques, which are by their very nature accompanied by diffusion, degrade the definition of device features or cause new problems such as increased leakage of semiconductor junctions (De Souza & Sadana, 1994; Hsieh *et al.*, 1994; Liu *et al.*, 1995). This may not be a major problem with current generation of semiconductors, but it is a serious obstacle for the production of next-generation ultrahigh-density, low-power semiconductor devices that have very narrow (≤ 0.2 μm) and very shallow (≤ 0.1 μm) implanted regions.

This article discusses research at the Naval Research Laboratory on the corrugation overstability, astrophysical jets, and—in the industrial applications area—a new semiconductor annealing technique called athermal annealing.

2. BLAST WAVE CORRUGATION OVERSTABILITY

Radiative blast waves, central in many astrophysical phenomena, are shocks in which the power lost through radiation affects the shock dynamics. A decelerating radiative shock can be subject to corrugations or ripples that oscillate and grow as a power law of time (Vishniac, 1983). These ripples grow because the force due to the thermal pressure of the shocked gas, which is perpendicular to the local shock front, is not necessarily parallel to the force from the ram pressure of the upstream gas, which is directed along the shock velocity vector. In shocks with sufficiently high compression, this imbalance of forces induces oscillatory movement of material within the shock shell. Parts of the shell that contain less mass slow down more than the parts of the shell that contain more mass and a growing oscillation ensues. In its nonlinear phase, knots or clumps of material may form with sizes similar to the thickness of the shocked shell (MacLow & Norman, 1993). The overstability is predicted to turn on when the adiabatic index of the gas, γ, is less than 1.2. The original impetus for studying this instability was an application to galaxy formation in the early universe, where shocks cooling by inverse Compton emission and subject to such oscillations would seed the initial conditions for gravitational collapse. Such ideas are less favored today because the predicted nonuniformities in the cosmic microwave background were not observed. However it is still possible that interstellar shocks cooling by atomic and molecular line emission subject to the aforementioned instability provide the initial condition for gravitational collapse and the subsequent birth of new stars, and that radiative shocks in other contexts, such as active galactic nuclei and supernova remnants, can provide the mechanism for local clumping of plasma.

To produce an overstable shock wave in the laboratory, a shock in 5 torr of xenon gas was generated by the expansion of ablation plasma from the surface of a laser-irradiated foil (Grun *et al.*, 1991). The foil, a 6-μm-thick sliver of polystyrene, was irradiated by a 5-ns pulse from an Nd-glass laser, which was focused to 3 TW/cm^2 on the foil's surface. Ablation plasma from the foil propagates supersonically into the background gas and, much like the products of a chemical explosion, forms a shock wave. As a control, a similar experiment was performed in nitrogen gas. We have verified through extensive experimentation that this laser-ablation method forms classical Taylor–Sedov shocks when the interaction between the ablation plasma and the gas is collisional, and when the mass of the swept-up ambient gas is greater than the mass of the ablation plasma. (For nitrogen, collisional coupling occurs at pressures exceeding 0.5 torr.)

We discovered that, in contrast to smooth and stable Taylor–Sedov shocks in nitrogen, shocks in xenon gas exhibited dramatic, temporally growing corrugations (Fig. 1). The amplitude of these corrugations was quantified by tracing and Fourier transforming the outer edge of the shock. Once the shock became Taylor–Sedov-like, the amplitude was found to grow as a power law in time, $A(k,t)/R(t) \approx t^{S(kR(t))}$, where $A(k,t)$ is the full amplitude of the mode with wave number k at time t, and $R(t)$ is the average radius of the shock boundary at t (Fig. 2). Clear growth was observed for modes satisfying $0.7 < \log(kR) < 2$. Maximum growth occurred for $\log(kR) = 1$, where $S = 1.6$, and minimum growth, with $S = 0.3$, occurred at $\log(kR) = 2$. Growth continued for about 275 ns, after which the amplitude de-

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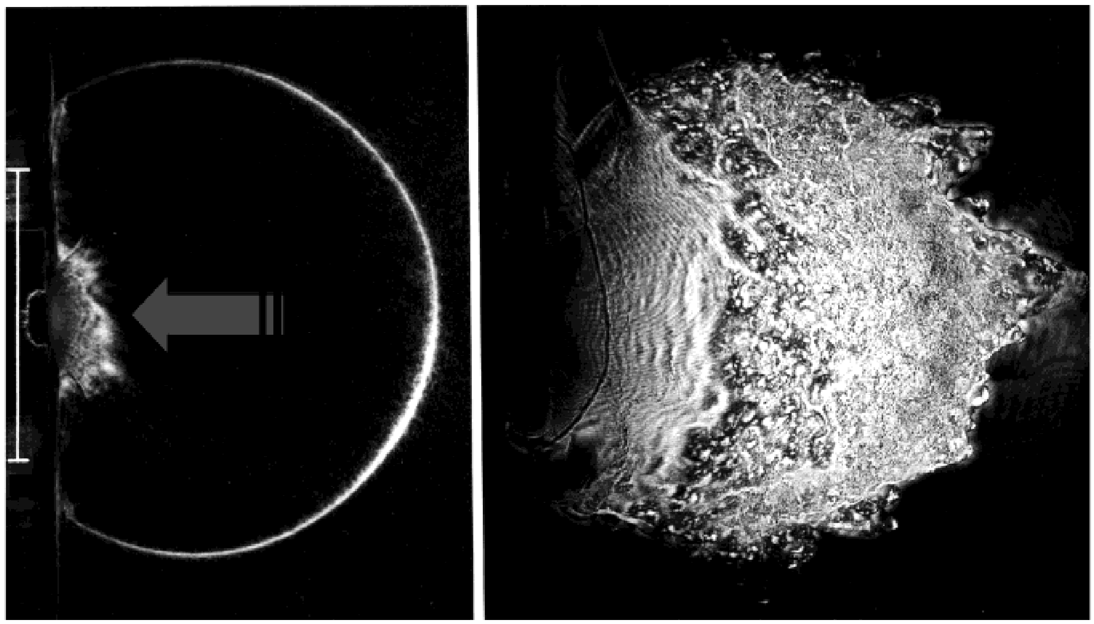

Fig. 1. Stable shock in ambient nitrogen (left) and overstable shock in ambient xenon (right). Both shocks were photographed at 243 ns after the laser pulse (arrow) irradiated the foil.

creased and the shock became smooth. γ in xenon was determined to be 1.06 and in nitrogen 1.3 (Grun *et al.*, 1991).

To explain the overstability, we found it necessary to perform detailed calculations of the radiative cooling of the shock fronts in nitrogen and xenon (Laming & Grun, 2002, 2003). The calculations produce a value for the adiabatic index γ that, when used in the hydrodynamic theory of Vishniac *et al.* (Vishinac, 1983; Ryu & Vishniac, 1987; Vishniac & Ryu, 1989) allows us to predict the overstability growth. Our major finding is that the shocked plasma must cool significantly during the shock transition, which is a distance on the order of the ion mean free path. Predicted growths are in very good agreement with our experiment.

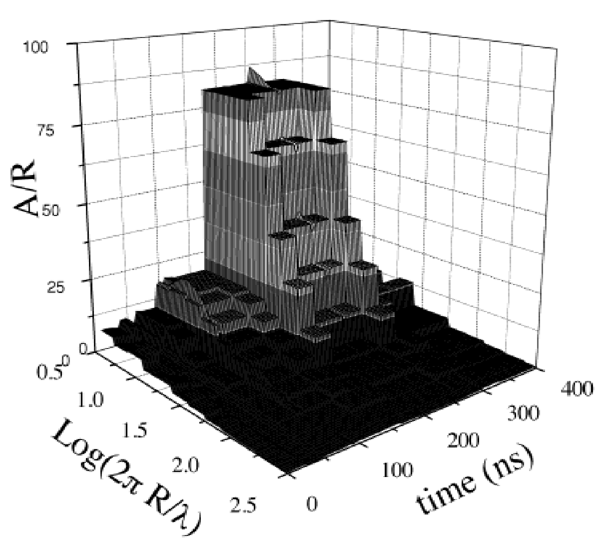

Fig. 2. Growth of the amplitude of the corrugation instability as a function of time and wavelength.

Details of the calculations are given in Laming and Grun (2002, 2003) and will not be repeated here. Suffice it to say that after calculating the ionization balance, temperatures, and densities through the shock front, an average γ is computed from the average density enhancement in the accumulated shell of shocked gas. The variations of γ with time behind the shock front for N and Xe are shown in Figure 3. Following shock passage, both gases cool and compress to $\gamma \sim 1.02$–1.03 by radiation and ionization losses. After cooling, the radiative efficiency of N is diminished by electron collisional depopulation of excited levels. Its power loss does not keep up with the energy deposited in the gas by photoionization, and so its temperature rises and the gas slowly expands. In contrast, Xe can still radiate at the high electron density and remains relatively cold and compressed. This is the fundamental reason why Xe blast waves are overstable and N blast waves are not. Using the values of γ and local Mach number evaluated relative to sound speed in the shock precursor, we evaluate the growth exponent real(s) using Vishniac & Ryu (1989). These growths are in good agreement with the observations in Grun *et al.* (1991).

3. ASTROPHYSICAL JETS

Jetlike structures have been observed in the remnants of supernovae, such as the radio image of SNR W50 and in X-ray imagery of the vela pulsar. Recent theories and calculations consider that the jet structures are not secondary by-products of supernovae explosions, but rather that they play a principal role in the disassembly of exploding stars

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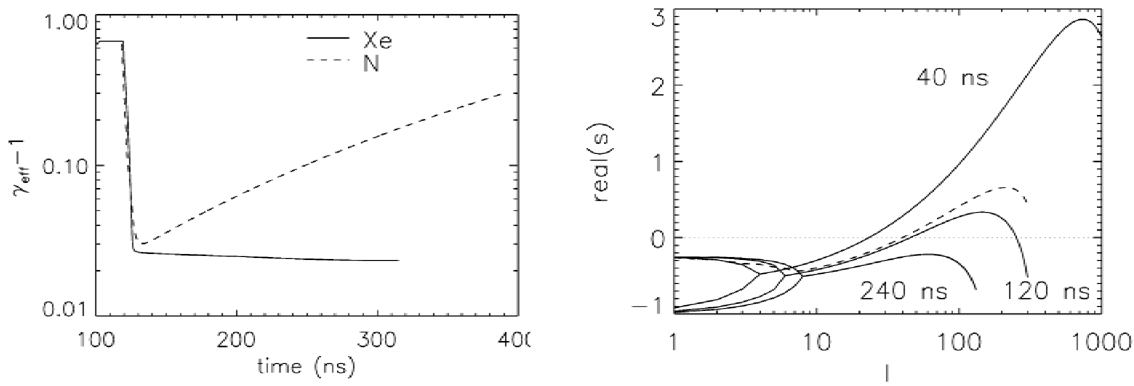

Fig. 3. Left: Evolution of γ with time for N (dashed line) and Xe (solid line). At 120 ns, following passage of the shock front, the plasma cools to $\gamma \sim 1.03$ by radiation and ionization losses. The Xe plasma stays at lower γ than N (i.e. stays dense) because it is more able to radiate the energy deposited by photoionization. N is less able to radiate at high electron densities due to collisional depopulation of excited levels, and so gradually heats up and expands behind the shock. This is the origin of the different stability properties of the two gases. Right: Plots (solid lines) of real(s) where the overstability grows as t^s, for Xe blast waves at 40, 120, and 240 ns after the laser pulse for a blast wave expanding with radius $R \approx t^{2/5}$. The dashed line shows real(s) averaged between 35 and 140 ns after the laser pulse.

(Khokhlov *et al.*, 1999). It is believed that two jets formed during the star's collapse shoot out in opposite directions from the star's interior, and that their interaction with star matter causes the star to explode. Another area where jets are believed to play a role is in star-forming accretion disks, where jets are thought to be a mechanism for removing rotational energy.

For a proper understanding and validation of theories of the type of astrophysical jets described above, it is necessary to perform experiments that simulate the interaction of plasma jets with stellar and interstellar matter. For proper scaling, it is necessary that the mach number of the laboratory jet, relative to its internal sound speed, be about 1–10 and that the jet to ambient gas density ratio is more than 1. Such parameters are readily achievable by hollow cones whose walls are accelerated from the outside by powerful laser pulses. The collapse of such cones, like the explosively driven shaped charges used since WWII, produces jets that can run into a low density gas or foam that simulates the stellar or interstellar matter. Unlike explosives, a laser driver can generate ultrahigh, megabar pressures and thus drive the jets to velocities 100 times faster then anything otherwise possible. The results of a preliminary experiment are shown in Figure 4.

4. ATHERMAL ANNEALING OF SEMICONDUCTORS

Athermal annealing (AA) is a new (Manka *et al.*, 1999) semiconductor annealing method that is much faster than thermal annealing and does not involve the direct application of thermal energy. Therefore, it is expected to be accompanied by far less diffusion than thermal annealing methods. In AA, a laser pulse focused to high power on a small spot on the surface of a doped semiconductor (thus far Si, GaAs, and InP) removes structural damage induced by dopant implantation and also electrically activates dopants in regions of the wafer *far outside* the laser spot where no heat is directly deposited. The electrical characteristics of athermal annealed samples are comparable to what is attainable with commercial furnace annealing. We conjecture that the annealing is caused by mechanical energy launched by laser-heated plasma into the wafer.

To demonstrate AA, a doped semiconductor sample is placed inside a vacuum chamber and irradiated by a pulse from a 1.06-μm wavelength, 5-ns FWHM duration, ~10-J

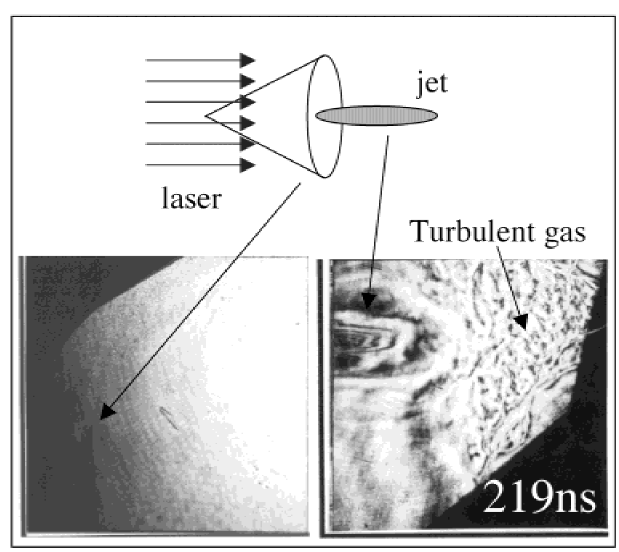

Fig. 4. Left: A 20-μm-thick plastic (CH) cone with a 74° full-cone angle mounted on stalk and ready to be illuminated by a 14-TW/cm^2 laser pulse. Right: Tip of the cone-produced jet pushing through about 10 mtorr of ambient gas driving turbulence in front of it. The photograph is a Schlieren image acquired at 219 ns after the cone was irradiated.

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laser pulse focused to a 1-mm-diameter spot on the sample surface. After laser irradiation, the sample is analyzed for changes in electrical activation, carrier density, mobility, resistivity, and crystal structure using diagnostics such as IR absorption spectroscopy (electrical activation), 4-point probing (resistivity), Hall effect measurements (electron mobility, electron concentration), Raman spectroscopy (crystal structure), X-ray topography (crystal structure), and secondary-ion mass spectroscopy (dopant diffusion). Unannealed and thermally annealed wafers are used as controls. Experiments to measure the mechanical energy in the sample and to correlate acoustic disturbances to the occurrence of annealing are now in progress.

An example of vastly reduced diffusion achieved by AA is shown in Figure 5. Here, AA was performed on a Czochralski silicon sample that was preamorphized with a germanium implant of 5 keV and a dose of 1×10^{15} cm^{-2}, followed by a $^{11}B^+$ implant at 3 keV and a dose of 1×10^{15} cm^{-2}. These doses and implant energies are representative of implants being considered for shallow junction fabrication processes. Control samples were thermally annealed at 900°C for 1 h in a N_2 atmosphere. The athermally annealed samples were subjected to a single laser pulse of approximately 7 J, 35 ns in duration, focused to a 2.5-mm-diameter spot. Annealing was observed in a circular area approximately 1 cm in diameter centered on the laser focal spot. Secondary ion mass spectrometry and infrared absorption measurements were then performed on all of the samples. As expected, significant diffusion is observed in the thermally annealed control samples. One parameter used to assess the degree of diffusion is the depth at which the concentration falls below a certain value. For these experiments, we are using a concentration value of 1×10^{18} cm^{-3} to determine the degree of diffusion. Using this value, the diffusion in the thermally annealed samples increases by a factor of approximately 3. By contrast, the amount of diffusion in the athermally annealed samples is significantly lower than in the thermally annealed samples. In fact, the profile of the athermally annealed samples is very similar to the as-implanted profile.

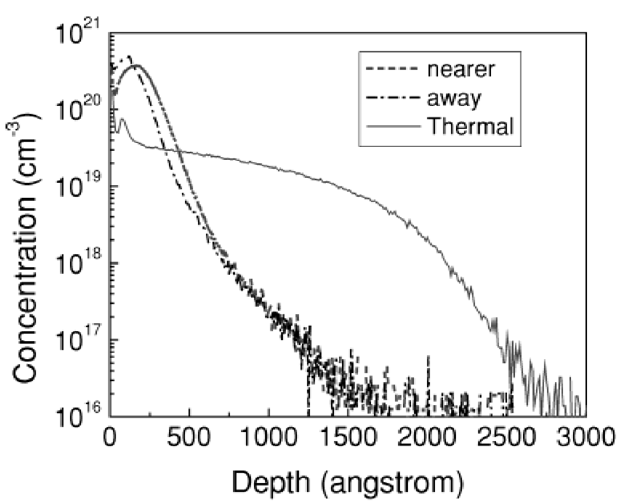

Fig. 5. Minimal dopant diffusion in athermal-annealed boron-implanted silicon. This graph shows the concentration of dopants as a function of depth in the silicon sample. The original boron dopant distribution (–·–·–·) differs little from the boron dopant distribution in athermal-annealed samples (- - - -). In sharp contrast, dopant distribution in thermally annealed samples (———) showed significant diffusion into the silicon wafer. The athermal-annealed and thermally annealed wafers had sheet similar resistivities of 267 Ω/□ and 243 Ω/□, respectively. (The sample was doped with boron at 3 keV and athermal-annealed by irradiation with a 7-J 35-ns laser pulse.)

5. SUMMARY

In summary, we have shown how laser-produced plasmas are used in two areas having vastly different spatial and temporal dimensions, namely astrophysics and industrial semiconductor production. We discussed experimental and theoretical studies of the corrugation instability in radiative shocks that are thought to play an important role in astrophysics. We found that accurate treatment of ionization and cooling microphysics is crucial to a quantitative understanding of the instability. Use of ionization equilibrium radiative losses will give the wrong answer! Effects of density on cooling rates are very important and distinguish Xe from N behavior in our case.

Laboratory simulations of astrophysical jets utilizing shaped-charge-like hollow cones have begun. Calculations and preliminary experiments indicate that the concept is feasible and that results can scale properly to astrophysical jets.

We have shown how laser-generated plasmas launch mechanical energy into doped semiconductor wafers, which, under certain circumstances, anneals and electrically activates the semiconductor in areas far outside the laser spot (thus far 1 cm^2). The process results in minimal dopant diffusion and may become an enabling technology for the production of next-generation ultrahigh-density, low-power semiconductor devices that have very narrow and very shallow implanted regions.

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