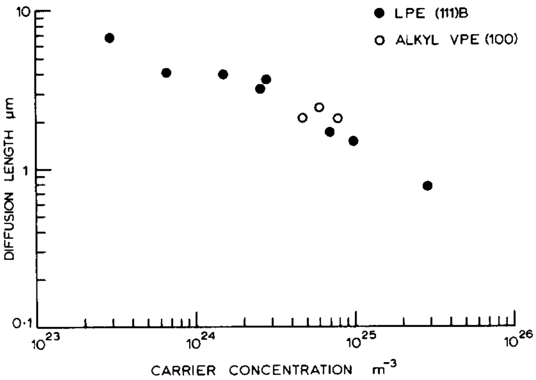

FIG. 1. The electron diffusion length in p-type GaAs grown by alkyl vapor-phase epitaxy and by liquid-phase epitaxy.

and this suggests that surface carbon contamination is not a serious drawback to this method of growth.

A diffusion model of a negative electron affinity photocathode[11] gives the quantum yield $Y(\lambda)$ for a reflection photocathode at wavelength λ as

$$Y(\lambda)=P[1-R(\lambda)]\alpha(\lambda)L/[1+\alpha(\lambda)L], \tag{2}$$

where P is the surface escape probability, $R(\lambda)$ the optical reflectivity, $\alpha(\lambda)$ the optical absorption coefficient, and L the electron diffusion length. P and L have been determined by fitting the measured quantum yields to Eq. (2) using published optical data for GaAs.[12] The values obtained appear in Table I, whilst the diffusion lengths are plotted in Fig. 1 together with data for the zinc-doped LPE material measured in the same equipment. It is clear from these data that the alkyl material has satisfactory minority-carrier properties with diffusion lengths equal to those of good-quality LPE material, whilst the escape probabilities of 0.29 to 0.37 are within the range of values measured on the (111)B LPE material at the same carrier concentration.

The results presented in this letter show that the alkyl system of vapor-phase epitaxy can produce high-quality GaAs, which is well suited to photocathode applications, and encourage its use in the growth of more complex transmission structures.

[1]R. L. Bell and W.E. Spicer, Proc. IEEE 58, 1788 (1970).
[2]D.G. Fisher, R.E. Enstrom, J.S. Escher, H.F. Gossenberger, and J.R. Appert, IEEE Trans. Electron. Devices 21, 641 (1974).
[3]M.B. Allenson, P.G.R. King, M.C. Rowland, G.J. Steward, and C.H.A. Syms, J. Phys. D 5, L89 (1972).
[4]R. U. Martinelli, Appl. Opt. 12, 1841 (1973).
[5]W.A. Gutierrez, H. L. Wilson, and E.M. Yee, Appl. Phys. Lett. 25, 482 (1974).
[6]H.M. Manesevit and W.I. Simpson, J. Electrochem. Soc. 120, 135 (1973).
[7]H.M. Manesevit, J. Cryst. Growth 22, 125 (1974).
[8]J.J. Uebbing, J. Appl. Phys. 41, 802 (1970).
[9]S.J. Bass, Third International Conference on Vapor Growth and Epitaxy, Amsterdam, 1975 (unpublished).
[10]V.W. Steward and C.H.A. Syms, J. Phys. 6, 14 (1973).
[11]G.A. Allen, J. Phys. D 4, 308 (1971).
[12]R.C. Eden, Stanford Technical Report No. 5221-1, 1967 (unpublished).

Measurement of intense magnetic fields associated with laser-produced plasmas

R. Serov* and M. C. Richardson

Division of Physics, National Research Council of Canada, Ottawa, Canada

(Received 7 August 1975; in final form 24 November 1975)

Measurements have been made with subnanosecond resolution of the azimuthal magnetic field spontaneously associated with plasmas produced by high-intensity (10^{12}–10^{14} W/cm^2) 1-nsec-duration CO_2 laser pulses. In addition to a distinct dependence on background argon gas pressure, it is found that the magnetic field displays a $1/r^2$ radial dependence, and its onset is synchronous with the initial formation of the plasma.

PACS numbers: 52.50.J, 52.70.D

Since the first observation of spontaneously generated magnetic fields in laser-produced plasmas,[1] a number of studies of this phenomenon have been reported.[2–5] Stamper *et al.*[3] have suggested that the spontaneous magnetic fields result from thermoelectric currents in the plasma associated with large temperature and density gradients, and also radiation pressure effects[6] existing during the early stages of the formation of the plasma. In addition, Bird *et al.*[4] conclude from their results that spontaneous magnetic fields may also be generated by density gradients in the plasma front, long after the termination of the laser pulse. The importance of the existence of these magnetic fields to the physics of laser-target interaction, particularly with respect to laser plasmas of fusion interest, has recently been addressed by several authors.[7–11] Extrapolation of the results of Stamper *et al.*[3] implies the possible existence of magnetic fields in the target region of several megagauss.[7,8] This has recently been confirmed by direct observation of Faraday rotation in plasmas produced by subnanosecond 1.06-μ laser pulses.[5] Fields of such magnitude would significantly affect the electron thermal conduction process, and other plasma-dynamic processes, and consequently play an important role in determining the temperature and density distributions within the plasma.[12] It has also been postulated that

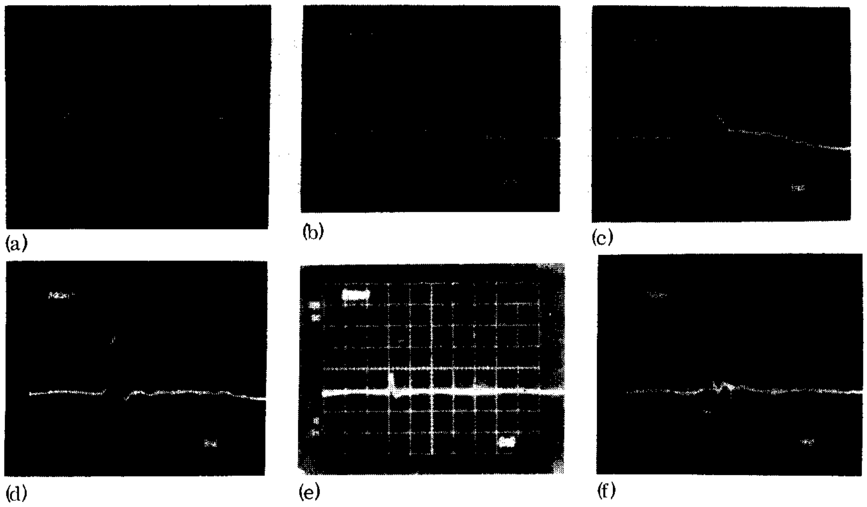

FIG. 1. Typical magnetic probe signals. (a) Magnetic probe situated 8 mm from plasma for laser energy of ~0.2 J focused onto a CH_2 target, 300 mTorr Ar gas; scale: 10 nsec/div. (b)—(e) Variation of the shape of the $\dot{B}$ signal observed from plasmas produced from an Al target, as a function of background argon gas pressure: (b) 170 mTorr, (c) 400 mTorr, (d) 1600 mTorr, (e) 4000 mTorr. Scale: 35 G/sq. div, 5 nsec/div. (f) Magnetic field signal recorded at pressures <20 mT. Laser energy of the order of 0.2 J, probe situated 8 mm from target.

they may play an important part in the generation of superthermal particles,[13] evidence for which has been found in a number of recent laser-plasma experiments.[14]

In the experiments reported here, measurements have been made of the magnetic field associated with plasmas produced under a variety of target and background gas conditions, by the focused output of a 1-nsec-duration CO_2 laser pulse of intense power.[15] These measurements were made with the aid of specially developed single turn coil differential magnetic probes[16] possessing subnanosecond temporal resolution, good sensitivity ($0.3\ V\,nsec\,G^{-1}$) as well as high discrimination (>300) against all forms of photoelectric and electronic noise. The magnetic probes were situated at various distances from the plasma, approximately in the plane of the target, and oriented so as to measure azimuthal magnetic fields about the laser beam axis generated at the time, or following, production of the plasma. The plasma was produced in a vacuum chamber by the CO_2 laser radiation focused at near normal incidence onto solid targets of Al or CH_2 by means of an NaCl lens of focal length 40 cm with maximum power densities in the ~120-μ-diam focal region of $\sim 9\times10^{13}$ W/cm^2.

The magnetic probe signal, which measures the temporal derivative of the magnetic field, typically consisted of a short pulse of rise time of 1—2 nsec and fall time <10 nsec, followed by a negative signal for 20—30 nsec. Figure 1 shows typical examples of the magnetic probe signal obtained from laser-irradiated CH_2 [Fig. 1(a)] and Al [Figs. 1(b)—1(f)] targets. It was verified that this signal was in fact that resulting from a transient magnetic field by rotating the magnetic probe by 180°, whereupon a similar signal identical in shape and amplitude, but opposite in polarity, was consistently observed. Tests were also made with the same probe situated at different positions about, though the same distance from, the focal spot, and showed that the magnetic field signal resulted from an azimuthally symmetric magnetic field. Under most background gas conditions the direction of this magnetic field corresponded to that which would be produced by a transient current source flowing in the direction of the target, i.e., in the same direction as that of the laser beam. In addition, and most significantly, careful measurements showed that the initial rise of the magnetic field signal coincided, to within <1 nsec, to the time of interaction of the short 1-nsec laser pulse with the target, irrespective of the distance of the magnetic probe from the focal point (up to a distance of several millimeters). Thus the magnetic field at all times measured resulted from the plasma behaving as an isolated transient current element rather than being one frozen into an expanding plasma.

The temporal dependence of the $\dot{B}$ signal as a function of background gas pressure, for constant laser and focusing conditions, on an Al target is shown in Figs. 1(b)—1(e). These oscilloscope traces show on an expanded time base the fast component of the $\dot{B}$ signal, indicating that the rise time of the resulting transient magnetic field decreases with increasing background gas pressure from ~10 nsec at a pressure of a few hundred Torr to ~1 nsec at 4000 Torr. An arrival time of ~10 nsec of the peak magnetic field at the probe would be consistant with the velocity of fast ions ($\sim 10^8$ cm/sec) observed from such plasmas.[14] However, the assumption of a correspondence between the fast-ion component and the resulting magnetic field would imply that at higher pressures, where the arrival time reduces to ~1 nsec, there existed ion components having much higher velocities. In addition, it was noted that although observation of this magnetic field signal was only resolvable at background pressures of about 20 mTorr, at pressures below this value, a small ultrashort magnetic field signal of opposite polarity was recorded. A typical example of this magnetic probe signal is shown in Fig. 1(f). In contrast to the magnetic field measured with a high density of background gas, this $\dot{B}$ signal, which may result from an effective transient electron flow into the target, has a very weak dependence on background gas pressure.

Since the magnetic probe measures the temporal derivative of the magnetic field, integration of the first half-cycle of the probe signal renders the maximum magnetic field recorded. Thus it was possible to measure the absolute value of the magnetic field recorded by the probe as a function of laser operating conditions, target material, background gas pressure, and distance

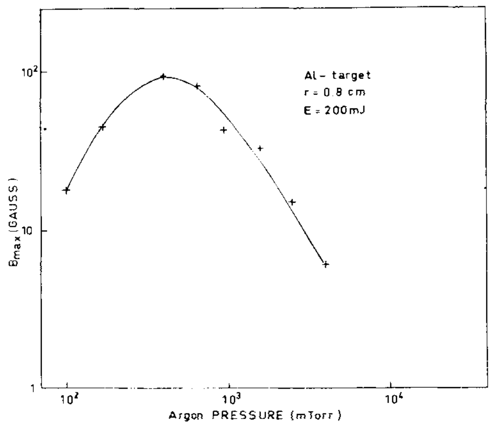

FIG. 2. Variation of peak magnetic field as function of background argon gas pressure for a laser energy of ~200 mJ focused onto a solid Al target. The probe was situated 8 mm from the plasma.

of the probe from the plasma. The variation of the peak magnetic field observed as a function of background argon gas pressure for a laser energy of ~0.2 J is shown in Fig. 2. In this case, the magnetic probe was situated 8 mm from the plasma. It can be seen that as the pressure of the background gas is increased, the recorded magnetic field initially increases to a maximum value for gas pressures of ~600 mTorr. As the pressure is further increased above this value, the magnetic field progressively decreases until the signal disappears below the detection limit at pressures above 6×10^3 mTorr. It is interesting to note that although there are strong differences between the appearance of the magnetic field signal in the present case and previous measurements, the pressure dependence and absolute magnitude of the field observed are similar to those found for spontaneous magnetic fields generated within plasmas produced by long (25 nsec) 1.06-μ laser pulses of energy ~7 J focused onto solid Al targets.[4] However, the radial dependence of the magnetic field, shown in Fig. 3 is strikingly different. As can be seen from Figs. 3(a) and 3(b), both the $\dot{B}$ signal and the absolute value of the magnetic field displayed an inverse square relationship with the radial distance of the probe from the plasma. Previous studies[3] of the spontaneous magnetic field induced within the plasma have indicated a different radial dependence. In the present case, the $1/r^2$ dependence of the magnetic field was measured for probe distances of 2 cm to 3 mm where probe magnetic fields in excess of 1 kG were observed. If this magnetic field is considered to originate from a small isolated source, and since it reaches its peak value in times much less than 10 nsec from the time of interaction with the target, it is relatively safe to extrapolate this dependence to the dimensions of the plasmas immediately after its creation. This would imply that close to the plasma surface there must exist magnetic fields of several hundred kilogauss.

In summary, evidence has been obtained for the existence of very large azimuthal magnetic fields associated with the formation of plasmas produced by high-intensity 1-nsec-duration CO_2 laser pulses in a background gas environ. The $1/r^2$ dependence of this magnetic field, and the synchronism of the probe signal with the time of interaction, indicate that the magnetic fields measured are those which are associated with the small isolated plasma at the focal spot. The magnitude of the magnetic field is found to depend strongly on the background gas pressure, and two principal regimes have been found to be operative. For background gas pressures <20 mTorr, the observed weak magnetic field, which is not strongly pressure dependent, could possibly be produced by a net flow into the target of superthermal electrons resulting from thermoelectric effects[13] or by collisionless electron conduction effects.[17] The explanation for the much larger magnetic fields observed at higher background gas pressures is at present also ambiguous. The creation of magnetic fields by thermoelectric currents within the plasma has been considered for some time, and recently their generation as a result of resonant absorption has been proposed.[18] However, other mechanisms, depending upon the magnetization of the electronic thermal conduction,[11] or upon the existence of the superthermal ions and elec-

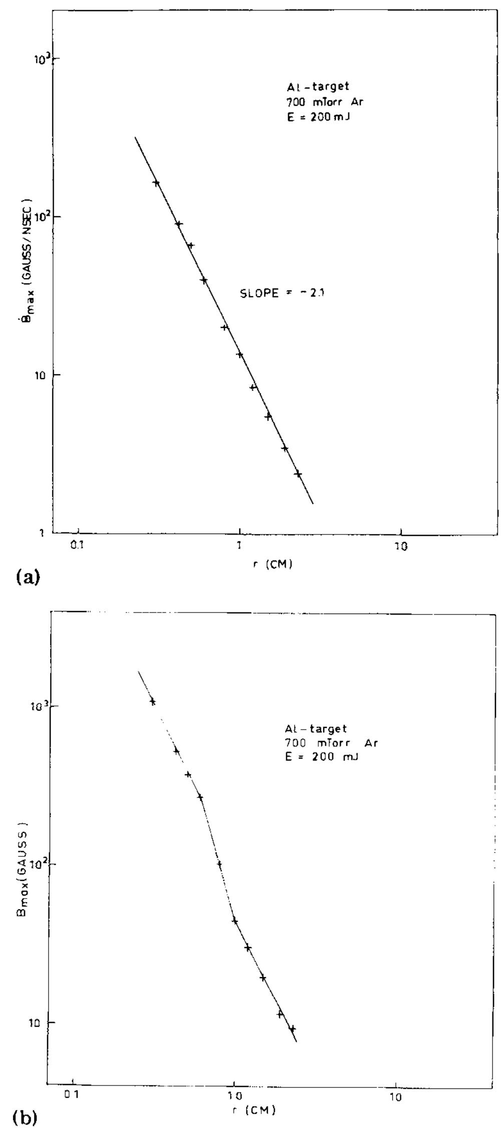

FIG. 3. Radial dependence of (a) the measured time derivative of the magnetic field and (b) the peak magnetic field.

trons known to exist in these plasmas, should also be considered.

The authors acknowledge useful discussions with Dr. A.J. Alcock, Dr. N.H. Burnett, and Dr. P.B. Corkum, and the continued technical assistance of P. Burtyn, K. Leopold, and W.J. Orr.

*Visiting scientist from the P.N. Levedev Physical Institute, Moscow, under an exchange agreement between the National Research Council of Canada and the Academy of Sciences of the USSR.

[1]V.V. Korobkin and R.V. Serov, Zh. Eksp. Teor. Fiz. Pis'ma Red. **4**, 103 (1966) [JETP Lett. **4**, 70 (1966)].
[2]G.A. Askar'yan, M.S. Rabinovich, A.D. Smirnova, and V.D. Studenov, Zh. Eksp. Teor, Fiz. Pis'ma Red. **5**, 116 (1967) [JETP Lett. **5**, 93 (1967)].
[3]J.A. Stamper, K. Papadoupoulos, R.N. Sudan, S.O. Dean, E.A. McLean, and J.M. Dawson, Phys. Rev. Lett. **26**, 1012 (1971).
[4]R.S. Bird, L.L. McKee, F. Schwirzke, and A.W. Cooper, Phys. Rev. A **7**, 1328 (1973).
[5]J.A. Stamper and B.H. Ripin, Phys. Rev. Lett. **34**, 135 (1975).
[6]J.A. Stamper and D.A. Tidman, Phys. Fluids **16**, 2024 (1973).
[7]J.A. Stamper, NRL Report No. 7411, 1972 (unpublished).
[8]J.B. Chase, J.L. LeBlanc and J.R. Wilson, Phys. Fluids **16**, 1142 (1973).
[9]M.M. Widner, Sandia Report No. SLA-73-0500, 1973 (unpublished).
[10]N.K. Winsor and D.A. Tidman, Phys. Rev. Lett. **31**, 1044 (1973).
[11]L.A. Bol'shov, Yu.A. Dreizin, and A.M. Dykhne, Zh. Eksp. Teor. Fiz. Pis'ma Red. **19**, 288 (1974) [JETP Lett. **19**, 168 (1974)].
[12]B.H. Ripin, P.G. Burkhalter, F.C. Young, J.M. McMahon, D.G. Colombant, S.E. Bodner, R.R. Whitlock, D.J. Nagel, D.J. Johnson, N.K. Winsor, C.M. Dozier, R.D. Bleach, J.M. Stamper and E.A. McClean, Phys. Rev. Lett. **34**, 1313 (1975).
[13]D.A. Tidman and J.A. Stamper, Appl. Phys. Lett. **22**, 498 (1973).
[14]See, for example, papers on high-power laser-plasma interaction, in *Laser Interaction and Related Phenomena, Vol.* 3, edited by H.J. Schwartz and H. Hora (Plenum, New York, 1974).
[15]M.C. Richardson, in *Laser Interaction and Related Phenomena, Vol.* 3(a), edited by H.J. Schwartz and H. Hora (Plenum, New York, 1974), p. 39.
[16]R. Serov, M.C. Richardson, and P. Burtyn, Rev. Sci. Instrum. **46**, 886 (1975).
[17]R.L. Morse and C.W. Nielson, Phys. Fluids **16**, 909 (1973).
[18]J.J. Thomson, C.E. Max and K. Estabrook, Report No. UCRL 76690, 1975 (unpublished).