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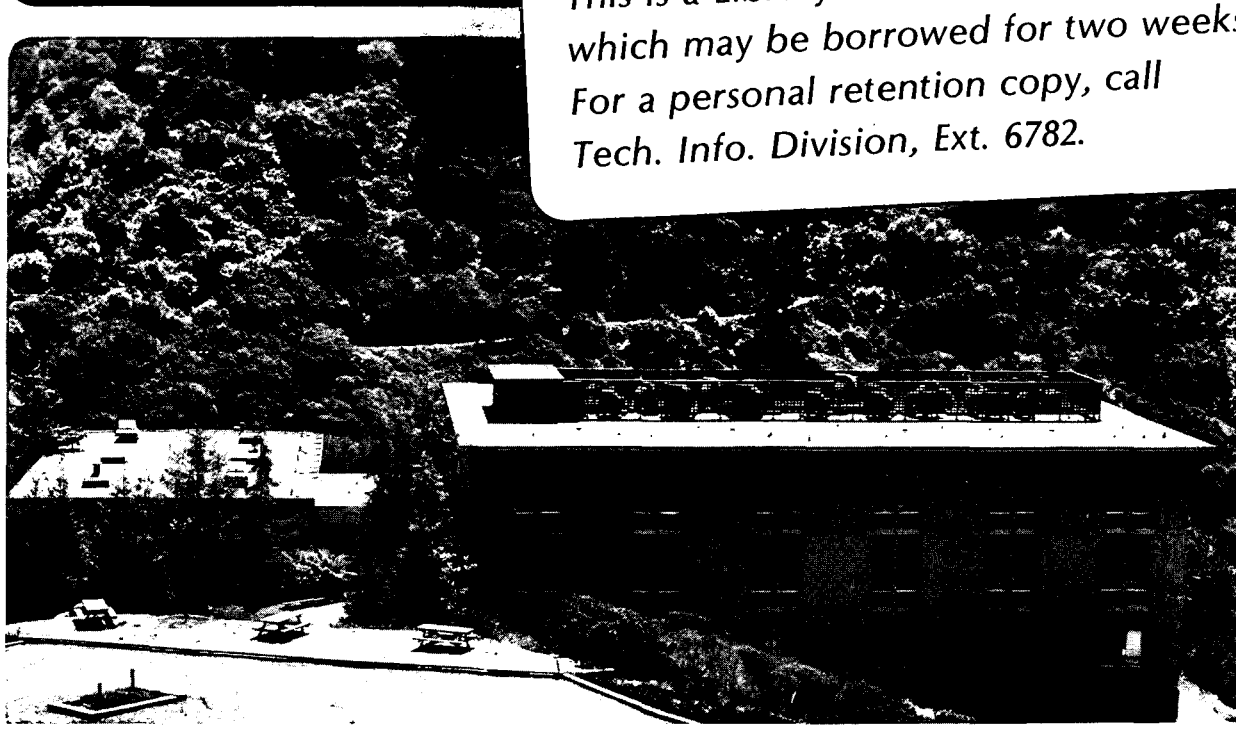

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High Resolution Structural Characterization of the Amorphous-Crystalline Interface in Se^+-Implanted GaAs

T. Sands, D.K. Sadana[+], R. Gronsky[++] and J. Washburn

Materials and Molecular Research Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

ABSTRACT

High resolution transmission electron microscopy (HRTEM) is applied to the characterization of the amorphous-crystalline interface in (100) GaAs implanted at room temperature with Se^+. The critical density of energy deposited by nuclear stopping is determined to be 11 $\pm$ 2 eV per GaAs molecule. This critical energy density is shown to be defined most naturally by a 50% amorphous-50% crystalline criterion. The amorphous-crystalline transition region was found to have a distinct two-phase nature. Both stacking fault nuclei and channeled damage cascades were detected in the as-implanted material.

INTRODUCTION

The advent of commercially available high resolution transmission microscopes (HRTEM) with "interpretable" point-to-point resolutions of $\sim$2.5Å and better has allowed the addition of HRTEM to the list of semiconductor characterization techniques. In particular, HRTEM is well suited to the study of interfaces and defects in ion-implanted

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[+]Now at Microelectronics Center of North Carolina, Research Triangle Park, North Carolina 27709

[++]Also at National Center for Electron Microscopy, Lawrence Berkeley Laboratory, Berkeley, California 94720

semiconductors, especially as a complementary technique to Rutherford backscattering/channeling (RBS/C), secondary ion mass spectrometry (SIMS), conventional TEM and depth-resolved Hall effect measurements. In this study, HRTEM has been applied to the structural characterization of the amorphous-crystalline interface in Se^+-implanted GaAs.

Recent papers suggest that the morphology of the amorphous-crystalline interface in implanted GaAs determines the morphology of the subsequently annealed material [1-3]. The RBS/C results of Bhattacharya et al [1] indicate that the amorphous-crystalline transition region has a finite width. This width is approximately equal to the width of the GaAs layer which can be regrown epitaxially at low temperature ($\sim$200°C) [1]. Similar results have been found by Grimaldi et al [2] for Si^+, S^+ and Ar^+ implanted GaAs. Further regrowth at temperatures less than $\sim$400° C produces a material with high defect density [2]. Based on x-ray diffraction results, Speriosu et al [3] have proposed the existence of extended defects near the amorphous-crystalline interface in as-implanted GaAs. These defects could act as nucleation sites for the large area defects which form during low temperature annealing [3]. The HRTEM results reported below are used to clarify the structural nature of the amorphous-crystalline interface, and to provide direct confirmation of the presence of defects in the crystalline material near the interface.

EXPERIMENTAL PROCEDURE

Wafers of Cr-doped semi-insulating (100) GaAs were implanted with 450 keV Se^+ at room temperature to a dose of 1×10^{14} cm^{-2}. Cross-section

specimens were prepared by cleavage on {110} . Cleaved strips were bonded face-to-face with epoxy and then thinned and polished mechanically to a thickness of ∿50μm. Final thinning was accomplished with 4 kV Argon ion milling using a specimen stage cooled by liquid nitrogen (20μA specimen current, 14° tilt). Electron microscopy was performed with a JEOL 200-CX (C_s - 1.2 mm, top entry stage) at 200 kV.

RESULTS AND DISCUSSION

In Fig. 1, a conventional bright-field image is compared with the energy deposited by nuclear stopping as calculated from the work of Brice [4]. Note that the bright-field image reveals dark bands at the surface (0 to 250 nm) and at the lower amorphous-crystalline interface (215-250 nm). The high resolution micrograph in Fig. 2 was taken from the upper portion of the lower dark band (depth 225 nm). This image shows that the dark bands are regions of an amorphous-crystalline transition composed of well-defined pockets of both crystalline and amorphous material. A numerical value for the critical density of energy deposited by nuclear stopping can be estimated from Fig. 1. This critical density for amorphization is generally defined as the energy density required for complete amorphization. However, the limits of the depth range which has undergone complete amorphization are ill-defined because of the statistical nature of the implantation process. A more meaningful and more easily measured quantity is the energy density required to produce a 50% amorphous-50% crystalline morphology. Figure 1 yields a value of 0.25 $\pm$ 0.05 keV/nm^3 (or 11 $\pm$ 2 eV/GaAs molecule) for the critical energy density as defined

above. This value is sensitive to dynamic annealing arising from the effects of ion implanation temperature and dose rate.

Figure 2 also reveals the presence of stacking fault nuclei in the transition region (see A in Fig. 2). These defects were commonly found at microfacets on small crystallites. This observation provides the first direct experimental evidence in support of the model proposed by Speriosu et al [3]. Bhattacharya et al [5] attempted to detect these defects using conventional TEM, however they concluded that such defects did not exist in their specimens. Obviously, the small size of these defects and their location at the amorphous-crystalline interface would make them difficult, if not impossible, to detect by conventional TEM. It is likely that these stacking fault nuclei are a result of dynamic annealing, although stresses in the amorphous-crystalline transition region could also contribute to their formation.

In addition to the stacking fault nuclei, the crystalline material in and directly below the transition region contains a high density of small defects with {111} habit (indicated by B in Fig. 2). The characteristic image of this defect is a row of image spots with reduced contrast on {111} having a projected defect length of 3.5 $\pm$ 0.5 nm. The image contrast shown in Fig. 3 persists through defocus.

The areal defect density to a depth of 300 nm is 5×10^{11} cm^{-2} $\pm$ 50% (assuming a specimen thickness of 20 nm) which is numerically equal to 0.5% of the total Se^{+} dose. Their crystallographic nature and density suggest that these damage zones may be due to channeling

of Se^+ ions at the end of their tracks, channeling of recoiled Ga or As, or clustering of any of these species.

The wealth of information accessible by HRTEM in the study of ion implanted semiconductors has been demonstrated with this case study. Combination of this technique with RBS/C, conventional TEM and other commonly applied techniques can provide an experimental basis for accurate quantitative models of amorphization and recrystallization of ion implanted semiconductors.

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FIGURE CATIONS

Fig. 1. Comparison of <110> cross-section micrograph of as-implanted GaAs with calculated energy deposited by nuclear stopping (solid line) and Se^+ concentration (dashed line) curves. Crystalline and amorphous GaAs are indicated by "c" and "α", respectively. Open circle marks the critical energy density for 50% amorphization.

Fig. 2. HRTEM image of upper portion of lower amorphous-crystalline transition region. ($\sim$225 nm below surface). Stacking fault nucleus (A) and channeled cascade (B) are described in text (arrow points to sample surfaces, defocus - 90 nm).

Fig. 3. HRTEM image of channeled damage cascade with 3.5 nm projected length (depth 270 nm, arrow points to sample surface, defocus - 90 nm).

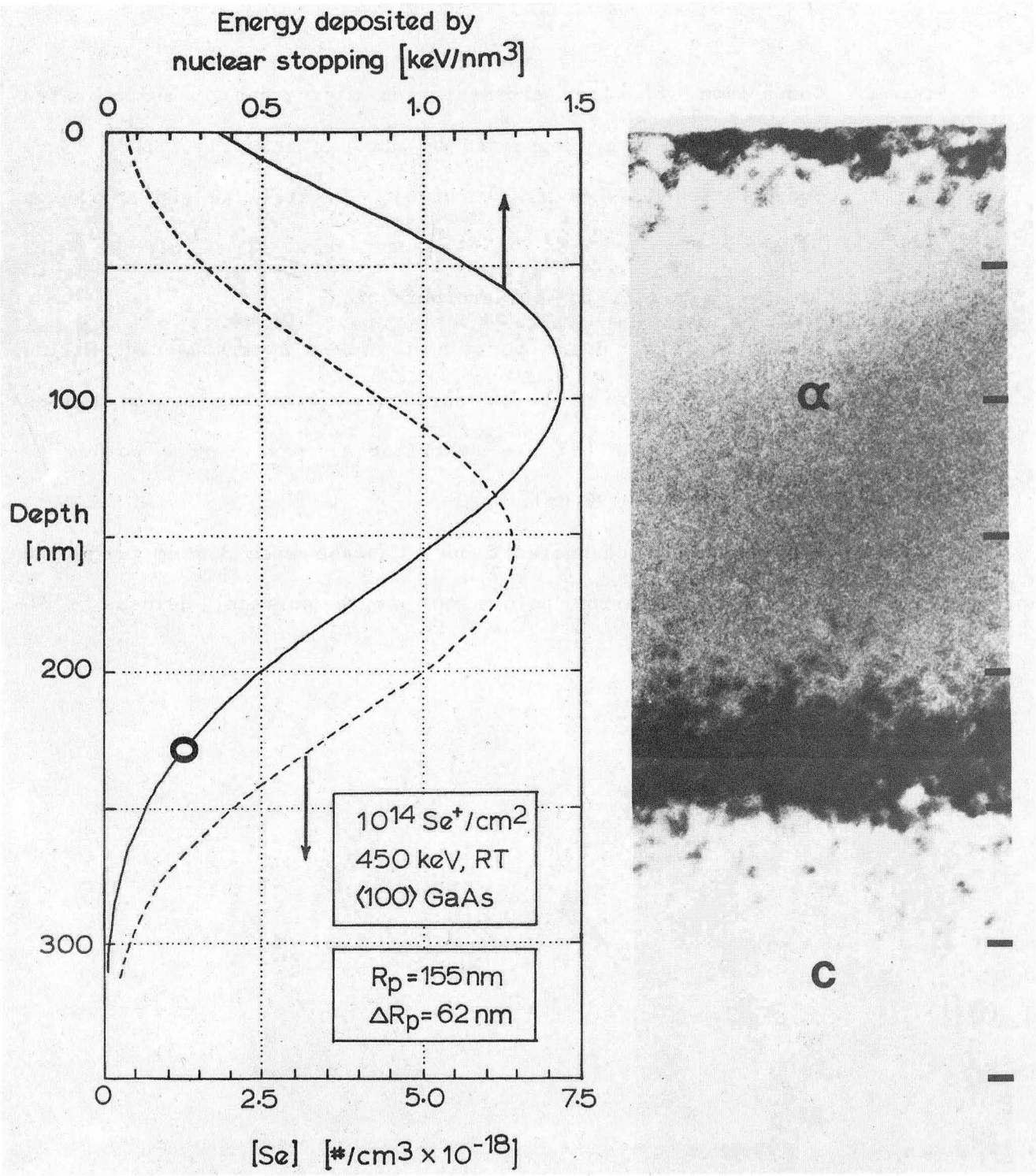

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Fig. 1

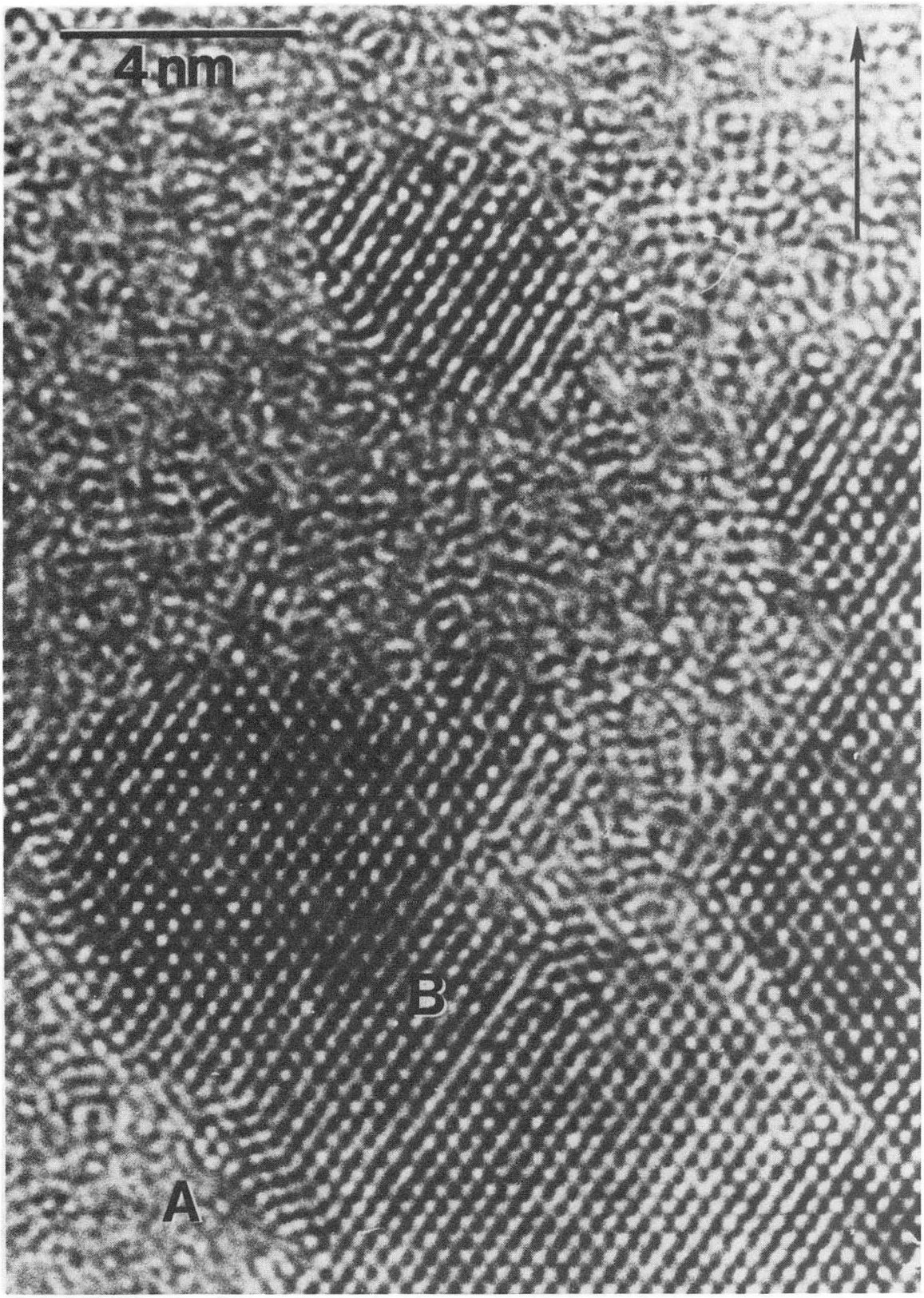

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Fig. 2

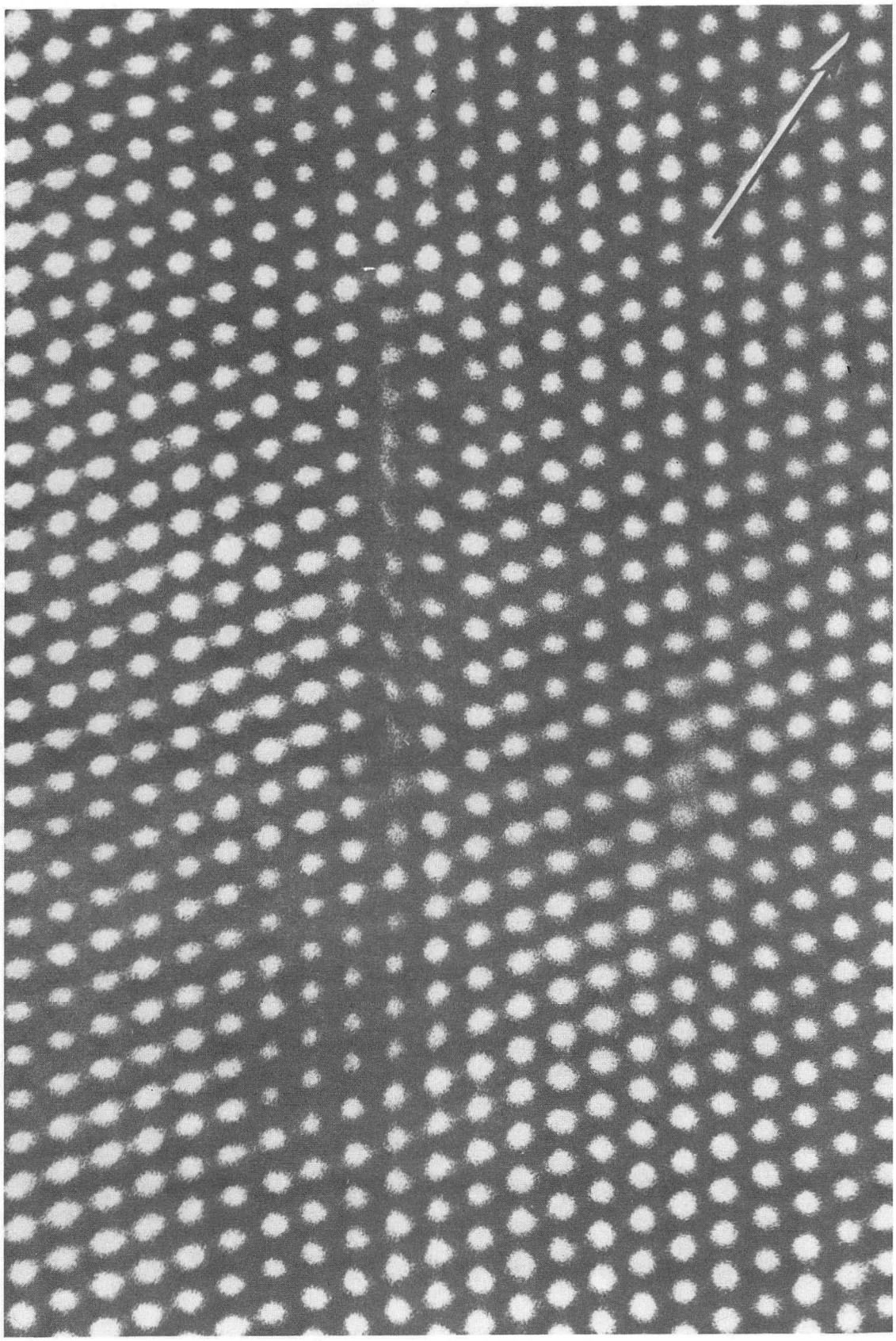

Fig. 3

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