in such a low-field region. The latter system is, on the other hand, an example of the magnetic superlattice films that show characteristics much less dependent on T below room temperature. The single crystal of the $(\mathrm{Nd,Sm})_{1/2}\mathrm{Sr}_{1/2}\mathrm{MnO}_3$ is more sensitive to low magnetic fields than the other compounds and has the largest MR value among them (Fig. 4), although the temperature region is limited (see also Fig. 3C) compared with those of the magnetic superlattice systems. The observed MR value, defined as $\Delta\rho/\rho(H)$, of the $(\mathrm{Nd,Sm})_{1/2}\mathrm{Sr}_{1/2}\mathrm{MnO}_3$ compound reaches 10^4 percent at 115 K under a magnetic field of 0.25 T and 4×10^4 percent at 125 K and 1.0 T. A MR effect of similar magnitude has been attained for thin films of $\mathrm{La}_{1-x}\mathrm{Ca}_x\mathrm{MnO}_3$ (4) and $\mathrm{Nd}_{1-x}\mathrm{Sr}_x\mathrm{MnO}_3$ (5) and for single crystals of the perovskite-type manganese oxides such as $\mathrm{Pr}_{1-x}\mathrm{Sr}_x\mathrm{MnO}_3$ ($x = 0.5$) (10), $\mathrm{Nd}_{1-x}\mathrm{Sr}_x\mathrm{MnO}_3$ ($x = 0.5$) (8), and $\mathrm{Pr}_{1-x}\mathrm{Ca}_x\mathrm{MnO}_3$ ($0.3 \leq x \leq 0.5$) (12). Nevertheless, the driving (saturation) magnetic field of $(\mathrm{Nd,Sm})_{1/2}\mathrm{Sr}_{1/2}\mathrm{MnO}_3$ is exceptionally low. The switching-like colossal MR accompanying the field hysteresis may have some potential for application to magnetoswitching materials and devices with memory function.

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6 November 1995; accepted 5 February 1996

Earliest Complete Dentition of an Anthropoid Primate from the Late Middle Eocene of Shanxi Province, China

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The complete lower dentition of a new species of the basal anthropoid genus *Eosimias* shows a combination of primitive and derived traits unknown in other living or fossil primates. Although certain dental traits are decidedly more primitive in *Eosimias* than in other basal anthropoids, numerous derived aspects of jaw and dental morphology support the anthropoid affinities of Eosimiidae. Eosimiids document an early structural phase in the evolution of higher primates. Phylogenies that derive early anthropoids from cercamoniine adapiforms are inconsistent with eosimiid anatomy. Because early fossil anthropoids are known from both Asia and Africa, the fossil record is presently insufficient to specify the continent on which this clade originated.

The extinct primate family Eosimiidae was first described in 1994 on the basis of fossils collected from the middle Eocene Shanghuang fissure-fillings of southern Jiangsu Province, China (*1*). Although fossils documenting several species of Eosimiidae are known, only one of these, *Eosimias sinensis*, has been described to date. *Eosimias sinensis* was originally interpreted as a member of an early basal radiation of anthropoid or higher primates, the taxon that today includes New and Old World monkeys, apes, and humans. Subsequently, the phylogenetic hypothesis that *Eosimias* is a basal anthropoid has been widely criticized, and several workers have even doubted its primate affinities (*2*–*4*). Here we describe a new eosimiid species, *Eosimias centennicus* (*5*), on the basis of fossils collected during May 1995 fieldwork in the Eocene Heti Formation, Yuanqu Basin, southern Shanxi Province, China (Fig. 1). These new specimens include the first complete lower dentition of eosimiid primates ever found. The anatomical information yielded by these fossils confirms the anthropoid affinities of Eosimiidae, thus providing new data on temporal, biogeographic, and phylogenetic aspects of anthropoid origins.

Historically, the Heti Formation in the Yuanqu Basin yielded the first Eocene vertebrates (including the primate *Hoanghonius stehlinii*) to be discovered in China (*6*). The mammalian fauna from the Heti Formation is usually correlated with the Sharamurunian Land Mammal Age of Asia (*7*) and is therefore probably late middle Eocene in age. The cricetid rodent *Pappocricetodon schaubii* from Locality 1 in the Zhaili Member of the Heti Formation (*8*), the same locality that yielded the eosimiid primate fossils described here, is morphologically more derived than is *P. antiquus*, which occurs in the Shanghuang fissure-fillings (*9*). Indeed, all available biostratigraphic evidence suggests that the new eo-

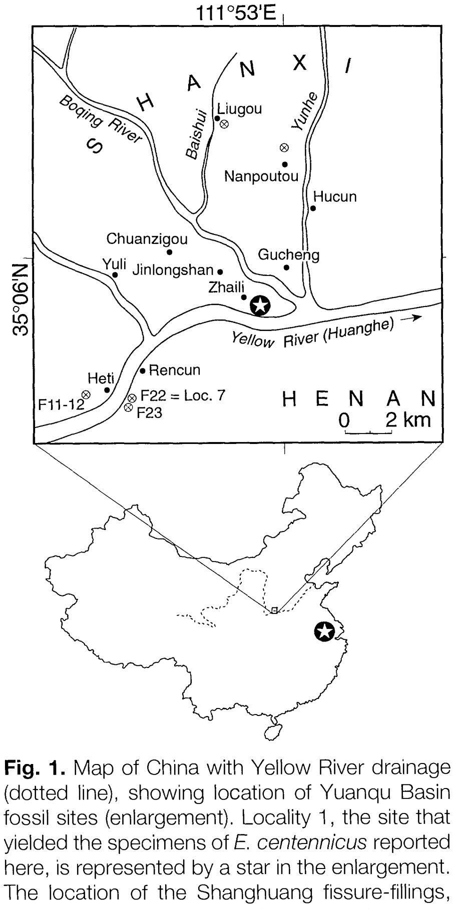

Fig. 1. Map of China with Yellow River drainage (dotted line), showing location of Yuanqu Basin fossil sites (enlargement). Locality 1, the site that yielded the specimens of *E. centennicus* reported here, is represented by a star in the enlargement. The location of the Shanghuang fissure-fillings, provenance of *E. sinensis*, is denoted by a star near the east coast of China.

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simiid fossils from the Yuanqu Basin are somewhat younger than *E. sinensis* from Shanghuang. This interpretation is consistent with the anatomy of the eosimiids themselves, because the dentition of *E. centennicus* is slightly more derived than that of *E. sinensis* (*5*).

The most complete specimen of *E. centennicus* from the Heti Formation consists of left and right dentaries of a single individual (Figs. 2 and 3). The symphysis and all lower tooth crowns (I_1 through M_3) are preserved on the right side, whereas only the crowns of the incisors are missing from the left. Additionally, the posterior part of the left dentary, including the coronoid process, condyle, and angle, is preserved.

The symphysis is unfused in *E. centennicus*, as is the case in other basal anthropoids such as *Catopithecus* from the Fayum, Egypt (*4*). In this primitive feature *Eosimias* also resembles many Eocene omomyids and adapiforms, although some adapiform taxa evolved fused mandibular symphyses in parallel with derived anthropoids. However, *Eosimias* differs from Eocene omomyids and adapiforms (and resembles other anthropoids) in having a symphyseal region that is dorsoventrally deep and anteroposteriorly abbreviated. In Eocene omomyids and adapiforms, the symphyseal region is more gracile in the dorsoventral dimension and is noticeably procumbent. Even adapiform taxa in which the symphysis is fused (for example, *Notharctus*, *Mahgarita*, and *Adapis*) show this primitive, gracile, and procumbent symphyseal morphology.

The two lower incisors are vertically implanted in *Eosimias*, and I_1 is smaller than I_2, as is the case in other early anthropoids for which the lower incisors are known. Vertical implantation of the lower incisors is undoubtedly a derived resemblance between *Eosimias* and other early anthropoids, because omomyids and adapiforms possess lower incisors that are invariably implanted in at least a slightly more procumbent position. The angle of implantation of the lower incisors is probably correlated with the differences in symphyseal morphology noted earlier. On the other hand, $I_1 < I_2$ likely represents the primitive condition in primates, because this character also occurs in adapiforms and omomyids such as *Washakius* (*10*).

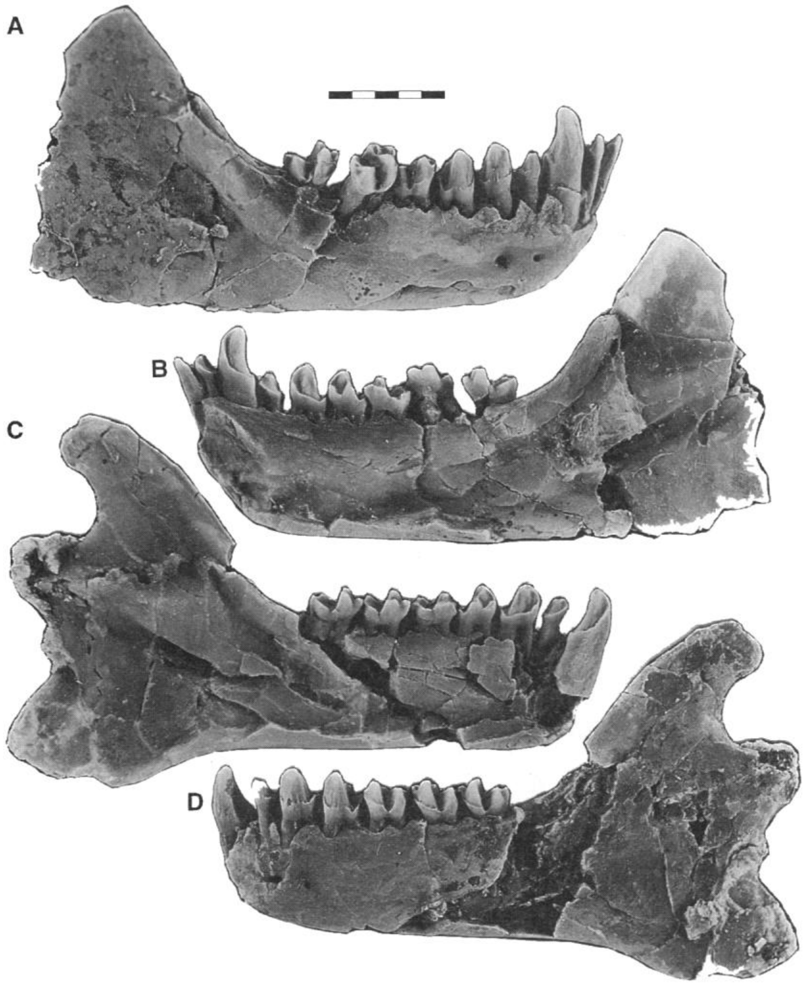

Fig. 2. *Eosimias centennicus* (holotype), associated left and right dentaries (IVPP V11000). (**A**) Right dentary preserving I_1 through M_3 in buccal view. (**B**) Right dentary in lingual view. (**C**) Left dentary preserving C_1 through M_3 in lingual view. (**D**) Left dentary in buccal view. Scale bar equals 5 mm.

The morphology of the lower incisor crowns has figured prominently in debates on anthropoid relationships (*4*, *11*). In *Eosimias*, I_1 and I_2 have slightly convex labial surfaces and moderately concave lingual surfaces. I_2 bears a lingual cingulid that completely surrounds the concave lingual surface of the crown. A similar lingual cingulid appears to have been present on I_1, but the morphology of this crown is slightly obscured by wear. Mesiodistally, both incisor crowns are widest near their bases. The apex of I_2 is pointed; a similar condition may well have characterized I_1. The roots of both incisors are remarkably long and are much wider in the labiolingual dimension than mesiodistally. The crowns of I_1 and I_2 in *Eosimias* differ morphologically from both the spatulate condition common in Eocene adapiforms and many anthropoids, and the more conical, pointed condition found in many omomyids (*11*, *12*). However, only subtle differences in lower incisor morphology distinguish *Eosimias* from such undoubted anthropoids as *Arsinoea*. The incisors of *Eosimias* are smaller relative to the cheek teeth than is the case in other basal anthropoids. It seems likely that the nonspatulate morphology and relatively small size of the lower incisors in *Eosimias* are primitive with respect to other anthropoids.

The lower canine in *Eosimias* is robust, projecting well above the crowns of the remainder of the lower dentition. The crown itself is slightly recurved and daggerlike. A well-defined lingual cingulid is continuous from the apex of the crown mesially to near its base, where the cingulid also lines the distal margin of the tooth. The broken left canine reveals that the root of this tooth is long and voluminous, extending virtually to the inferior margin of the dentary.

Eosimias centennicus possesses three lower premolars (P_2 through P_4), as do other basal anthropoids and many omomyids and adapiforms. However, primitive omomyids and adapiforms retained an additional lower premolar (P_1) that was lost at some point in anthropoid phylogeny (*13*). Also as in other basal anthropoids and all omomyids, P_2 in *Eosimias* is single-rooted rather than double-rooted. In contrast, P_2 is double-rooted in primitive adapiforms, although such derived adapiforms as *Mahgarita* convergently attained the single-rooted condition. The crown of P_2 is diminutive in *Eosimias*, only slightly larger than that of I_2. In this respect, *Eosimias* differs from many other basal anthropoids (for example, *Arsinoea*, *Serapia*, and many platyrrhines), but it is unclear whether the relatively small P_2 of *Eosimias* is primitive or derived with respect to other basal anthropoids. The morphologically simple crown of P_2 is dominated by a single cusp, and the crown as a whole is slightly canted mesially. Weak mesial and distal crests emanate from the apex of the P_2 protoconid, and a cingulid lines the lingual and distal bases of the crown.

Both P_3 and P_4 are obliquely oriented in the tooth row, with the mesial root labial in position with respect to the distal root. This condition was apparent on the basis of the alveoli of P_3 and the crown of P_4 in *Eosimias sinensis* (*1*), although some workers have questioned this (*2*). The crowns of P_3 and P_4 are similar in many respects, but P_4 is more nearly molariform in having a distinct paraconid and strong metaconid. In contrast, the trigonid of P_3 bears only a protoconid. P_3 further differs from P_4 in having a mesiodistally shorter talonid heel without a distinct hypoconid cusp. The crowns of both P_3 and P_4 bear weak, discontinuous labial cingulids and are slightly exodaenodont, as is common among basal anthropoids. A complete and well-defined lingual cingulid occurs on P_3.

The lower molars of *E. centennicus* do not differ appreciably from those preserved in *E. sinensis*. Therefore, only M_3, which was previously unknown in Eosimiidae, is described here. As is the case on M_1 and M_2, the trigonid of M_3 bears three well-defined cusps. The paraconid is remarkably large and cuspidate and is well separated mesially from the metaconid. In having the M_2 and M_3 paraconids and metaconids widely splayed (not connate), *Eosimias* differs from most adapiforms and omomyids. Although several other basal anthropoids retain lower molar paraconids, none of these taxa possess lower molar paraconids that are as robust as those of *Eosimias*. However, the smaller M_3 paraconid in *Serapia* does resemble that of *Eosimias* in being widely splayed from the metaconid. The M_3 trigonid is appreciably wider than the talonid, an uncommon condition in primates but one that is frequent in early anthropoids (*2*). The hypoconulid lobe of M_3 is highly abbreviated (both mesiodistally and buccolingually), and the entire distolingual margin of the talonid is reduced in comparison with omomyids and adapiforms. Similar reduction of the hypoconulid lobe and distolingual margin of M_3 occurs in other basal anthropoids (for example, *Arsinoea*, *Serapia*, and *Catopithecus*).

Posteroinferiorly, the dentary of *Eosimias* exhibits a rounded angle that is not developed into a projecting angular process, as is common among omomyids and adapiforms. In this derived character, *Eosimias* closely approximates other basal anthropoids. The articular surface of the condyle is broken, and the condyle is situated only slightly below the level of the relatively gracile coronoid process.

Like *E. sinensis*, *E. centennicus* was a tiny primate. Mean estimates of body mass for *E. centennicus*, based on regressions of body mass against M_1 area in living primates (*14*), are 91 to 179 g, depending on the regression model chosen. Thus *E. centennicus* was roughly the same size as the smallest extant anthropoid, *Cebuella pygmaea*. Its relatively low-crowned, bluntly crested cheek teeth suggest that *E. centennicus* subsisted primarily on a diet of fruits, supplemented with insects (*15*).

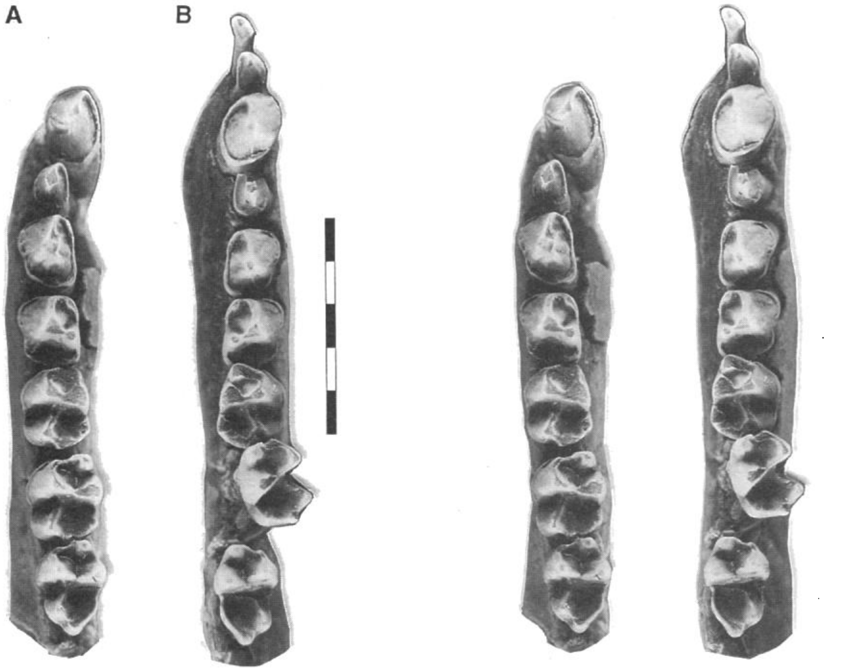

Fig. 3. *Eosimias centennicus* (holotype), associated left and right dentaries (IVPP V11000). (**A**) Left dentary preserving C_1 through M_3 in occlusal view (stereopair). (**B**) Right dentary preserving I_1 through M_3 in occlusal view (stereopair). Scale bar equals 5 mm.

The original description of *Eosimias* as a basal anthropoid was based on fragmentary lower jaws preserving the crowns of P_4 through M_2 and alveoli for other tooth loci (*1*). Partly as a result of this incomplete knowledge of the dentition of *Eosimias*, its affinities with anthropoids have been widely disputed (*2–4*). The new fossils reported here make *Eosimias* one of the few Eocene primates to be represented by its complete lower dentition. As such, several additional derived characters of *Eosimias* are now known that reinforce the hypothesis that *Eosimias* is a basal anthropoid. These include (i) an anteroposteriorly abbreviated, dorsoventrally deep symphysis; (ii) vertically implanted lower incisors; (iii) large projecting canines; (iv) P_3 and P_4 being slightly exodaenodont and obliquely oriented in the tooth row; (v) the M_3 trigonid being appreciably wider than the talonid; (vi) the hypoconulid lobe on M_3 being reduced both mesiodistally and buccolingually; and (vii) a rounded, nonprojecting angular region providing expanded area for insertion of pterygoid muscles. All of this new anatomical information corroborates the original hypothesis that *Eosimias* is a basal anthropoid, whereas none of the new data point toward alternative phylogenetic reconstructions (that is, there are no crossing synapomorphies). We conclude that *Eosimias* is indeed a basal anthropoid. Alternative phylogenetic reconstructions for this taxon have erred in emphasizing its retention of primitive dental traits (such as lower molar paraconids). Although it is undeniable that *Eosimias* is more primitive than any other fossil anthropoid in several respects, symplesiomorphy alone is no reason to deny its anthropoid affinities.

The phylogenetic relationships of anthropoids have been debated for many years (*1–4, 10, 16–18*). One current hypothesis is that anthropoids are derived from cercamoniine adapiforms (*3, 4, 16, 17*), but it conflicts with the anatomy of *Eosimias*, which is unlike that of adapiforms in any meaningful way. If we are correct in interpreting *Eosimias* as a basal anthropoid, the hypothesis that anthropoids evolved from adapiforms can be rejected (*1*). An adapiform ancestry for anthropoids is also difficult or impossible to reconcile with the large body of neontological data suggesting that *Tarsius* is the nearest living relative of anthropoids (*19*). Moreover, early fossil anthropoids are now known to antedate many of the cercamoniine adapiforms that are alleged to have been their ancestors (*1, 2, 20*). Advocates of the view that anthropoids are derived from cercamoniine adapiforms have often complained that alternative hypotheses of anthropoid origins rely on the assumption that a long interval of anthropoid history remains undocumented paleontologically; that is, that undoubted anthropoids evolved from a poorly known third group of early Cenozoic primates that were neither adapiforms nor omomyids (*17*). We submit that Eosimiidae represent this third group of early Cenozoic primates, amply demonstrating that the anthropoid clade was distinct from both Strepsirhini (including Adapiformes) and Tarsiiformes (including Omomyidae) by the middle Eocene if not earlier.

The fossil record of early anthropoid primates has been greatly augmented in recent years and is now sufficient to demonstrate that by the middle Eocene, higher primates ranged from western Algeria (*2*, *20*) to eastern China. This wide geographic range and the high taxonomic diversity of early anthropoids imply that the anthropoid clade is far more ancient than most workers have assumed. Nevertheless, this great antiquity for the anthropoid clade is consistent with the paleontologically documented antiquity of its likely sister group, the Tarsiiformes (*18*). Robust paleobiogeographic hypotheses regarding the continent of origin for Anthropoidea—either Asia or Africa—must be based on better paleontological data than are currently available.

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5. Order Primates, Suborder Anthropoidea, Family Eosimiidae, *Eosimias centennicus*, n. sp. **Holotype**: IVPP V11000, associated left and right dentaries of a single individual preserving right I_1 through M_3 and left C_1 through M_3 (Figs. 2 and 3). Dental measurements (in millimeters) for the right dentary are as follows: I_1 mesiodistal length (L) 0.60, labiolingual width (W) 0.45; I_2 L 0.90, W 0.80; C_1 L 1.70, W 1.40; P_2 L 1.00, W 0.85; P_3 L 1.60, W 1.40; P_4 L 1.70, W 1.45; M_1 L 1.95, W 1.60; M_2 L 1.95, W 1.70; and M_3 L 2.35, W 1.55. **Type locality**: Locality 1, the "River Section" locality of Zdansky (6), Zhaili Member, Heti Formation, Yuanqu Basin, Shanxi Province, China (35°04.95′N, 111°50.99′E). **Hypodigm**: The holotype; IVPP V11001.1, right dentary preserving P_3 through M_3; and IVPP V11001.2, right dentary preserving P_4 through M_2. **Known distribution**: Late middle Eocene of Shanxi Province, China. **Diagnosis**: Slightly larger than *E. sinensis*. P_4 differs from that in *E. sinensis* in having a trigonid with a distinct paraconid and a stronger metaconid. The P_4 metaconid is higher and more mesial in position than in *E. sinensis*. **Etymology**: In commemoration of the centennial of the Carnegie Museum of Natural History, celebrated in 1995–96.
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20 December 1995; accepted 23 January 1996

Imprint Lithography with 25-Nanometer Resolution

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A high-throughput lithographic method with 25-nanometer resolution and smooth vertical sidewalls is proposed and demonstrated. The technique uses compression molding to create a thickness contrast pattern in a thin resist film carried on a substrate, followed by anisotropic etching to transfer the pattern through the entire resist thickness. Metal patterns with a feature size of 25 nanometers and a period of 70 nanometers were fabricated with the use of resist templates created by imprint lithography in combination with a lift-off process. With further development, imprint lithography should allow fabrication of sub–10-nanometer structures and may become a commercially viable technique for manufacturing integrated circuits and other nanodevices.

The development of low-cost, high-throughput lithography techniques with sub–50-nm linewidth resolution is essential for the future manufacturing of semiconductor integrated circuits and the commercialization of electronic, optoelectronic, and magnetic nanodevices. Numerous technologies are under development. Scanning electron beam lithography has demonstrated 10-nm resolution (*1*); however, because it exposes point by point in a serial manner, the current throughput of the technique is too low to be economically practical for mass production of sub–50-nm structures. X-ray lithography has demonstrated 20-nm resolution (*2*) in a contact printing mode and can have a high throughput, but its mask technology and exposure systems are currently rather complex and expensive. Lithographies based on scanning proximal probes, which have shown a resolution of about 10 nm, are in the early stages of development (*3*).

In this report, we demonstrate an alternative lithographic method, imprint lithography, that is based on compression molding and a pattern transfer process. Compression molding is a low-cost, high-throughput manufacturing technology that has been in use for decades and features with sizes of >1 μm are routinely imprinted in plastics. Compact disks based on imprinting in polycarbonate are one example. Other examples are imprinted polymethylmethacrylate (PMMA) structures with a feature size on the order of 10 μm (*4*) and imprinted polyester patterns with feature dimensions of several tens of micrometers (*5*). However, compression molding has not been developed into a lithographic method to pattern semiconductors, metals, and other materials used in semiconductor integrated circuit manufacturing.

Using imprint lithography, we achieved a minimum feature size of 25 nm and a period of 70 nm in a resist >100 nm thick. We then fabricated 25-nm metal patterns by means of imprint lithography and a lift-off process. We believe that with further development, imprint lithography may become a commercially viable lithography

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