Magnetic and magneto-optical properties and domain structure of Co/Pd multilayers

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ABSTRACT

The domain structure of Co/Pd(1.6/6.3 Å)xN multilayers and its relation to the bulk magnetic properties of the samples were studied. The Co/Pd multilayeres were deposited by rf and dc magnetron sputtering onto different substrates. It was found that magnetic and magneto-optical properties and domain structure of the multilayers were affected by total film thickness and substrate condition. Magnetization, coercivity and anisotropy of the films decreased significantly as the film thickness dropped below 100 Å. However, Kerr rotation angle had a maximum at the same thickness. The width of the domain structure increased with the decrease of the film thickness attaining the single domain state at N=10. The initial curves in Co/Pd multilayers were found to depend on demagnetization process. The samples demagnetized by in-plane field showed the largest difference between initial curves and the corresponding parts of the loops. Different domain structures were observed in the samples demagnetized by perpendicular and in-plane magnetic fields.

I. INTRODUCTION

Multilayered films of Co/Pt and Co/Pd are promising materials for magneto-optical (MO) recording[1,2]. Compared to amorphous rare earth-transition metal alloys [3] currently used in commercial MO disks the multilayers are attractive for their superior corrosion resistance [4] and larger Kerr effect signal at short wavelengths [5] (<500 nm), where higher density recording is possible. Co/Pt multilayers have generally been considered more attractive than Co/Pd because of their larger Kerr rotation angle. Co/Pt is deficient, however, in coercivity. The coercivity of Co/Pd multilayers is considerably higher than that for Co/Pt [6]. The coercivity plays an important role in the recording process, since it governs the domain size, shape and stability during readout. Any fluctuations in coercivity may cause an inhomogeneity in domain shape, which in turn contributes to recording noise. The study of coercivity mechanisms in the multilayered structures is also of great importance from the fundamental point of view. The coercivity is closely related to magnetic anisotropy of thin films as well as to the microstructure parameters of the magnetic media such as interface quality, growth orientation, crystallite size, distribution of easy axis for individual crystallites and so forth. The shape of magnetic hysteresis loops, initial curves and domain structure also strongly depend on microstructure of the films. Consequently, the investigation of domain structures in multilayered films and their relation to hysteresis loops and initial curves can help in understanding the origins of coercivity in these films.

The present work is devoted to investigation of domain structures in Co/Pd(1.6/6.3 Å)xN

multilayers of varying thickness fabricated on different substrates, and their relation with hysteresis loops and initial magnetization curves.

II. EXPERIMENTAL

Multilayers of Co/Pd were fabricated by sputtering in Ar at a pressure of 20 mTorr onto various substrate conditions. The Co and Pd layers were deposited by rf and dc magnetron sputtering, respectively. Four different conditions were chosen, namely the multilayers were deposited onto Si(111) substrate, Si(111) etched (80A) by Ar, unetched SiN film which was deposited onto Si(111) and etched SiN film on Si(111). The thickness of SiN film was 850 A. For all the cases, individual layer thicknesses of Co and Pd were 1.6 Å and 6.3 Å, respectively. During deposition the substrate was kept at ambient temperature. The Pd layer was the first deposited onto substrate. The number of Co/Pd pairs, N, was 50 for all types of the substrates, and 6, 10, 20, 30, 40 for the etched SiN substrate (see table 1). Last letters in the sample ID mean substrate condition, and a number before the letters is attributable to the number of Co/Pd pairs. For example, sample ID S30ESiN means that substrate is etched SiN layer and the film has 30 Co/Pd pairs.

The measurement of magnetic properties of the samples was carried out by vibrating sample magnetometry in fields up to 14 kOe. The area of the samples for calculation of magnetization was measured using an optical microscope with digitizing image capability. Magneto-optic loops and initial curves were measured in our magneto-optic loop tracer [7] in fields up to 20 kOe. The constants of perpendicular anisotropy were determined using data

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obtained from the MO loop tracer with in-plane applied field [8]. Domain structures were observed with the help of polarizing optical microscope using a 100x objective (oil immersion type). The observations were recorded with a PC-based frame grabber that allowed image processing for noise reduction, image segmentation and image thresholding [9]. A single-pole, conical tip electromagnet capable of producing a maximum field of 5 kOe, was mounted under the microscope's XY stage to provide the necessary fields for domain growth and contraction.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. Domain structure and substrate condition

Our observations of domain structure in Co/Pd multilayers indicate that shape of the domains and their growth strongly depends on the substrate conditions and the total thickness of the film. In Fig.1 are shown the domain structures developing in (Co/Pd)x50 multilayered films fabricated on different substrates. The films S50ESi, S50USiN and S50ESiN show domain wall motion dominated magnetization process. Domain structure in the films initially saturated by the field of 20 kOe starts to develop from randomly distributed points. These points are believed to be some defects which facilitate creating a domain wall. Expansion of the domain in the magnetic field close to the coercive field looks like development of maze-like structure with very narrow domains. This behavior proves that DW coercivity is smaller than nucleation coercivity. The domain structure in the film deposited onto unetched Si substrate is quite different (Fig.1d). The remagnetization in this film occurs due to nucleation process. With the

increase of the magnetic field the entire film is covered with domains of opposite magnetization; thus the wall coercivity in this film is greater than nucleation coercivity. The magnetic properties of (Co/Pd)x50 multilayers are shown in table 1. It follows from this table that the macromagnetic parameters like M_s and H_c are very similar. K_u is about two times smaller for samples fabricated on unetched substrates. The lower value of K_u in the films on unetched substrates allows to demagnetize the samples with in-plane field of 20 kOe. The same in-plane field, applied to (Co/Pd)x50 films, fabricated on etched Si and SiN substrates, is not able to demagnetize the samples.

The authors of [10] measured the roughness of etched and unetched Si and SiN substrates as well as microstructure of Co/Pt multilayers fabricated on the substrates. They showed that the dispersion angle for <111> orientation of crystallites has the largest value for samples on unetched Si substrates. The presented in [10] magneto-optic loops indicate that the magnetization process in Co/Pt film on unetched Si substrate is nucleation dominated as in our case for Co/Pd film on the similar substrate. So, we can assume, that general microstructural properties of Co/Pt and Co/Pd multilayers on Si and SiN substrates are similar. Hence, the microstructure of the samples seems to be responsible for the type of magnetization process. The film with low perpendicular anisotropy and big dispersion angle of easy axes shows nucleation dominated magnetization. Samples with high anisotropy and low dispersion angle of easy axes show wall-motion dominated magnetization process.

B. Domain structure and film thickness

Figure 2 shows the magnetic and magneto-optic properties of (Co/Pd)xN films of different thicknesses, deposited onto etched SiN substrates, as functions of film thickness. The magnetization of the samples remains the same for N from 50 to 20 decreasing slightly for N=10 and 6. The coercivity decreases starting from 40 layers and reaches very low value of 85 Oe for N=6. Kerr rotation has a maximum for N=10, which is attributable to interference effects [11]. Anisotropy constant K_u decreases with the decrease of film thickness, approaching a value of $7x10^5$ erg/cc for N=6. Especially big drop in K_u value occurs at film thicknesses below 120 Å. The authors of [11] showed that this region of film thicknesses corresponds to formation of continuous film structure. For a Co/Pt film with the thickness t of 30 Å the distinct island structure was observed. On the contrary, the film with t= 150 Å had a continuous structure which was formed of very fine crystalline grains with the grain size below 100 Å in diameter.

Figure 3 represents the domain structures in (Co/Pd)xN multilayers of different thicknesses deposited onto etched SiN sublayer. With the decrease of the total thickness of the films the domain width of maze-like structure increases approaching the single domain state at N=10 and dropping again for N=6. The dependence of domain width on film thickness is shown in Fig.4. It is known from the domain theory [12] that the domain structure of the films with uniaxial magnetic anisotropy is effected by film thickness, t, and, in very thin films, single domain structure is attained. In a uniform film with strong perpendicular anisotropy the critical thickness at which the transition from a stripe domain to a single domain occurs is estimated by the formula [11]:

$$t_c = 16.8\sigma/\pi^4 M_s^2$$

where $\sigma=4(AK_u)^{0.5}$ is domain wall energy density, M_s is saturation magnetization, A - exchange stiffness, K_u - anisotropy constant. Using experimental data for K_u and M_s and assuming $A=10^{-7}$ erg/cm we can estimate t_c at about 200 Å. Experimental results indicate that in Co/Pd multilayers this value is about 100 Å. This discrepancy may be attributed to the fact that in the multilayered structures the effective exchange stiffness constant A can be lower than in pure ferromagnet because of the inclusion of nonmagnetic layers of Pd. The appearance of maze-like structure again in (Co/Pd)x6 multilayers can be explained by significant decrease in K_u constant (Fig.2a), so t_c is becoming lower than actual thickness of multilayered film with N=6.

C. Domain structure and initial curves

Measurements of the magneto-optic loops and initial curves have shown that the shape of the initial curve in Co/Pd multilayers strongly depends on the demagnetization procedure (Fig.5). If we demagnetize the sample by a perpendicular field of the same direction as for measuring the initial curve, the initial curve quickly approaches the corresponding point on the magneto-optic loop and goes along it up to saturation value. If we demagnetize the sample by a perpendicular field of opposite sign or by in-plane field the initial curve goes faster than the corresponding part of the magneto-optic loop and approaches the saturation value in lower magnetic fields. This difference between loop and initial curve is greater for samples demagnetized by in-plane magnetic field. In Fig.6 are shown domain structures in S10ESiN and S06ESiN films developed both by perpendicular and in-plane magnetic fields. Usually if we demagnetize by a perpendicular field, the width of the domains is comparable to that for domain

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structure expanding in the same sample . However if we demagnetize by in-plane fields, the width of domains is noticeably smaller than that for developing domain structure. The most striking difference is observed for S10ESiN film (Fig.6a,b) where single domain state is attained. After demagnetization by in-plane field of 20 kOe the film is covered by submicron domains.

As mentioned earlier, the initial curves for samples demagnetized by perpendicular fields of opposite directions are somewhat different. To determine the source of this difference we performed the following experiment: First, the domain structure was allowed to develop in the magnetic field in one direction (see Fig.7a). Then the reverse magnetic field was applied for several seconds to contract the structure (Fig.7b). The values of both magnetic fields were fixed. Finally, the difference of the two images was obtained (Fig.7c). The experiment has shown that the required field to start shrinking the structure in Fig.7a is lower than the opposite field needed to expand the structure. Figure 7c shows that the contraction occurs along the length of the walls, rather than at domain tips.

The difference in the initial curves for different demagnetized states can originate from pinning of DW on inhomogeneities in the films [13]. If we continue to expand a domain wall we need more field the DW to overcome energy barriers caused by a chain of pinning sites, which the DW has already approached. If the domain shrinks, the DW has some freedom to move between adjacent chains of pinning sites. So, the field required to shrink the DW is lower than that to expand the domain. Demagnetization by in-plane field produces much smaller domains. They arise randomly without any correspondence to pinning sites. In this case the domain walls have even more freedom to move. Moreover, small diameter facilitates collapse

of the domains. Therefore the initial curve for the films demagnetized by in-plane field goes much faster than that in the films, demagnetized by perpendicular field.

IV. CONCLUSION

It was found that magnetic and magneto-optical properties and domain structure of Co/Pd multilayers were affected by total film thickness and substrate conditions. Both wall motion- and nucleation-dominated processes were observed in the samples fabricated on different substrates. Magnetization, coercivity and anisotropy of the films decreased significantly as the film thickness dropped below 120 Å. The width of the domain structure increased with the decrease of film thickness, attaining the single domain state at $N=10$. The initial curves in Co/Pd multilayers were found to depend on the process by which demagnetization had been attained. The samples demagnetized by in-plane field showed the largest difference between initial curve and the corresponding parts of the loop. Different domain structures were observed in the samples demagnetized by perpendicular and in-plane magnetic fields.

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Table 1: Co/Pd(1.6/6.3 Å)xN samples

Sample ID	Number of layers	Substrate	M_s(emu/cc)	Θ_k(deg)	H_c(Oe)	K_u(x10^6 erg/cc)
S06ESiN	6	Etched SiN	320	0.23	85	0.7
S10ESiN	10	Etched SiN	374	0.29	636	3.9
S20ESiN	20	Etched SiN	424	0.25	1549	6.2
S30ESiN	30	Etched SiN	408	0.22	2431	6.8
S40ESiN	40	Etched SiN	405	0.19	2995	7.1
S50ESiN	50	Etched SiN	435	0.17	2990	7.5
S50USiN	50	Unetched SiN	402	0.16	2553	3.6
S50ESi	50	Etched Si	404	0.13	3075	5.5
S50USi	50	Unetched Si	392	0.11	3080	3.3
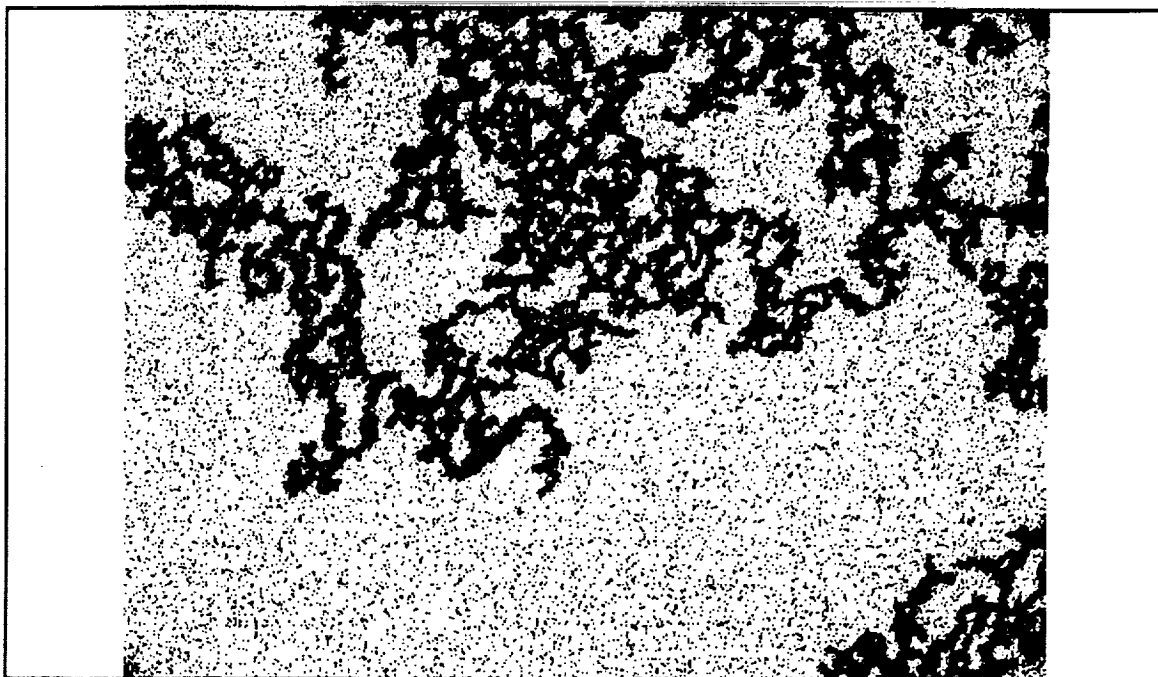
Figure 1a. Domain structure in Co/Pdx50 multilayered film,
deposited onto etched SiN layer, developing at H=2.8 kOe.

⊢ 10μm ⊣
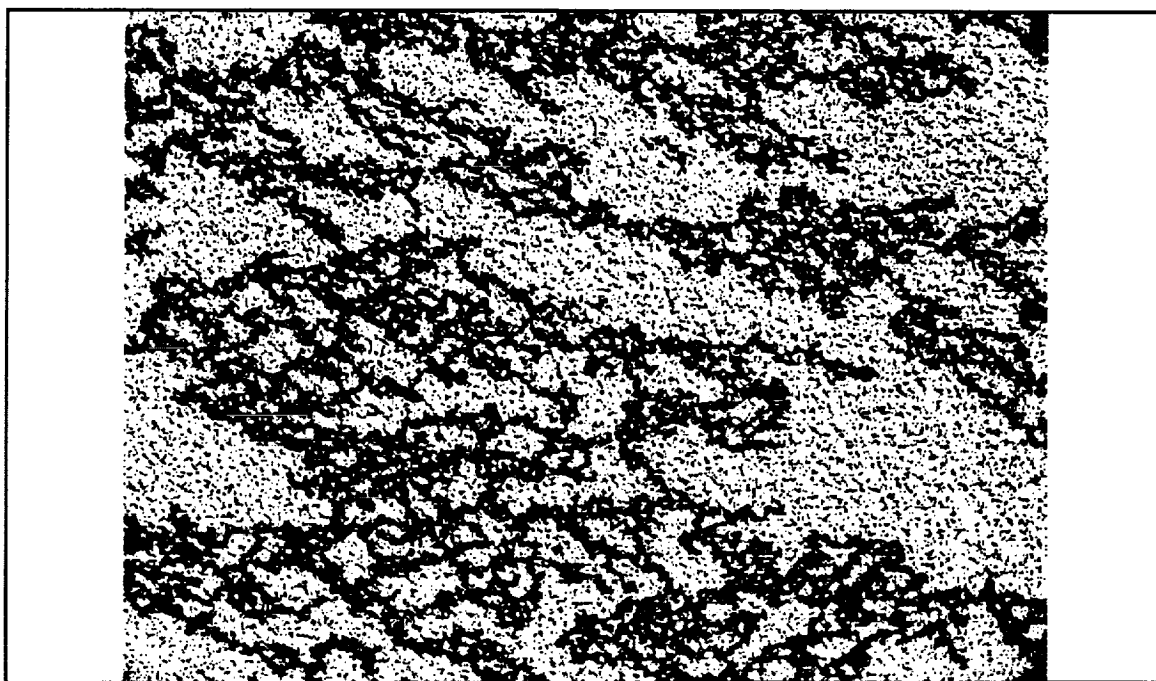
Figure 1b. Domain structure in Co/Pdx50 multilayered film,
deposited onto unetched SiN layer, developing at H=2.29 kOe.
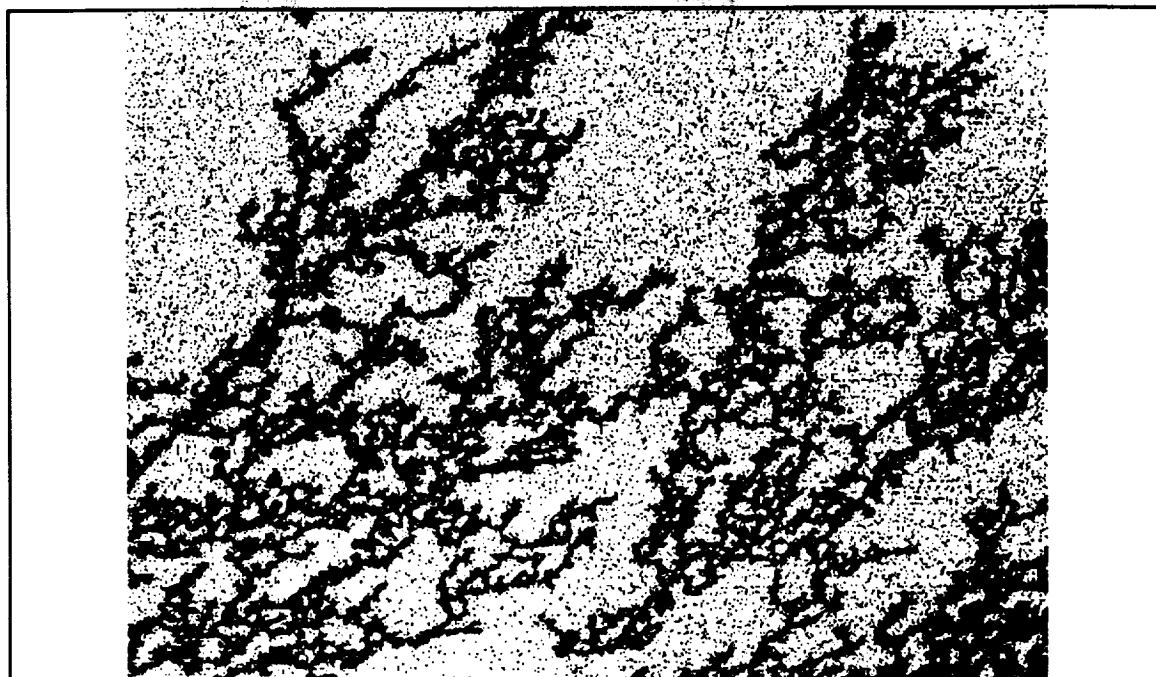
Figure 1c. Domain structure in Co/Pdx50 multilayered film,
deposited onto etched Si substrate, developing at H=2.8 kOe.

⊢ 10μm ⊣
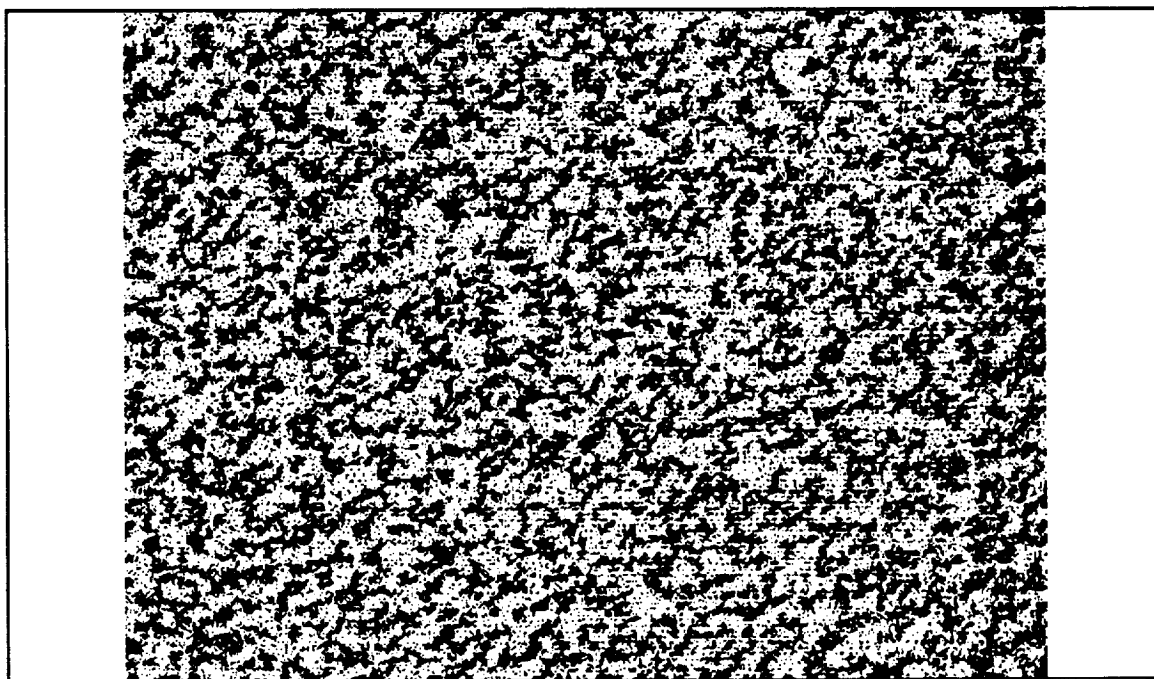
Figure 1d. Domain structure in Co/Pdx50 multilayered film,
deposited onto unetched Si substrate, developing at H=2.67 kOe.
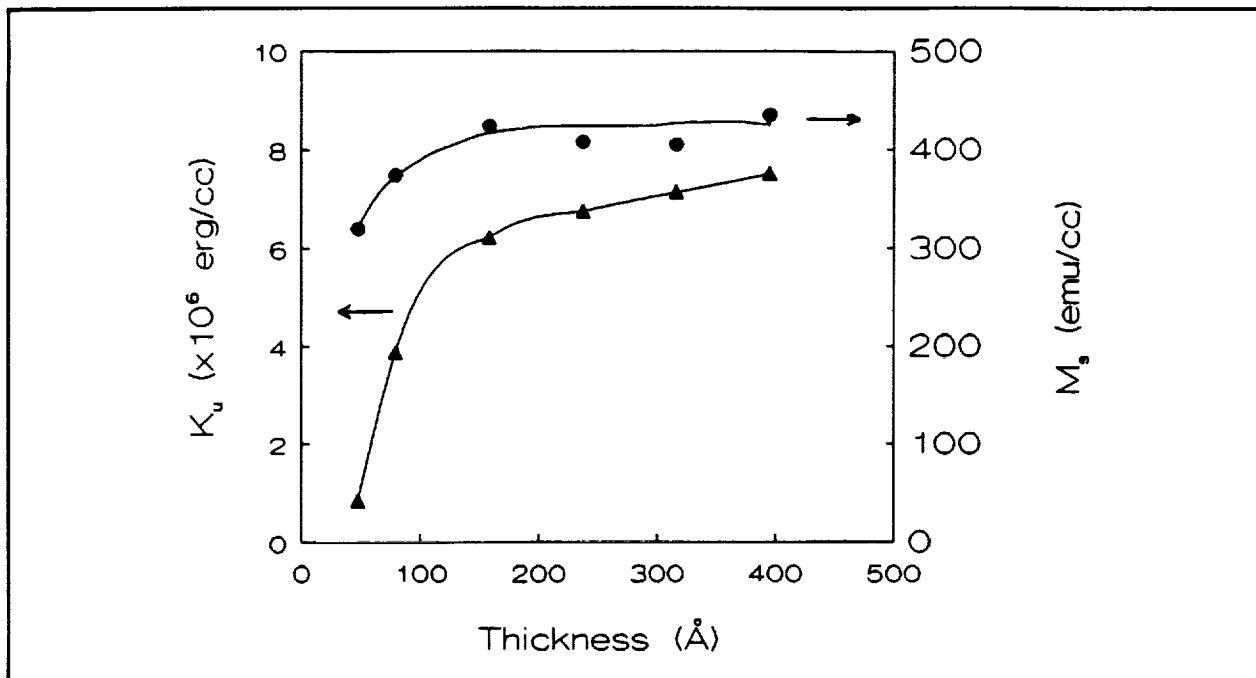
Figure 2a. Dependence of magnetization and anisotropy constant on the thickness of Co/Pd multilayers.
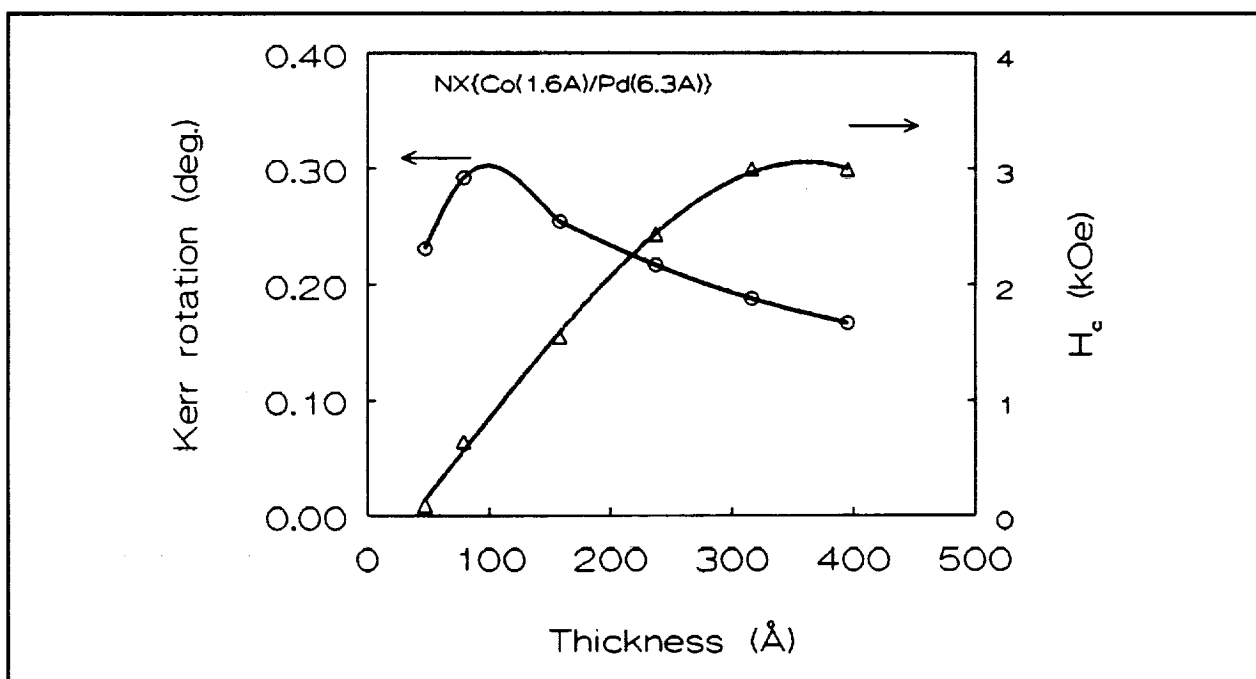
Figure 2b. Dependence of Kerr angle and coercivity on the thickness of Co/Pd multilayers.
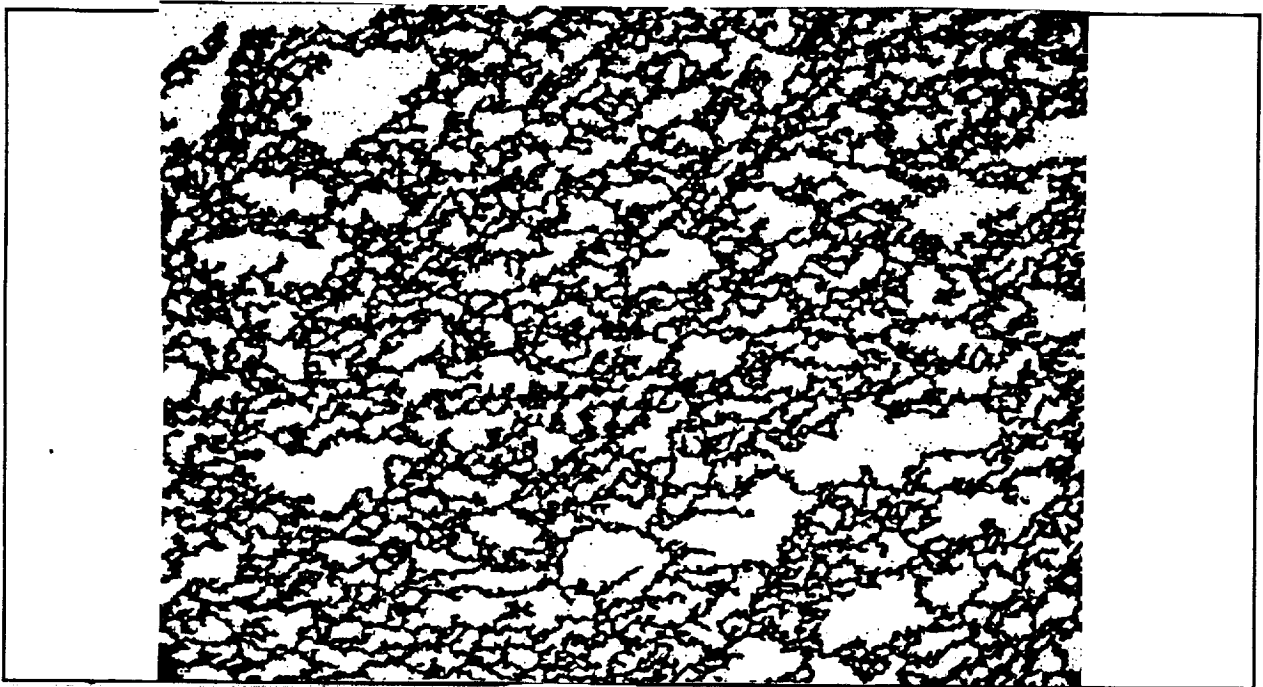
Figure 3a. Domain structure in S50ESiN sample developing at H=2.8 kOe.

⊢ 10μm ⊣
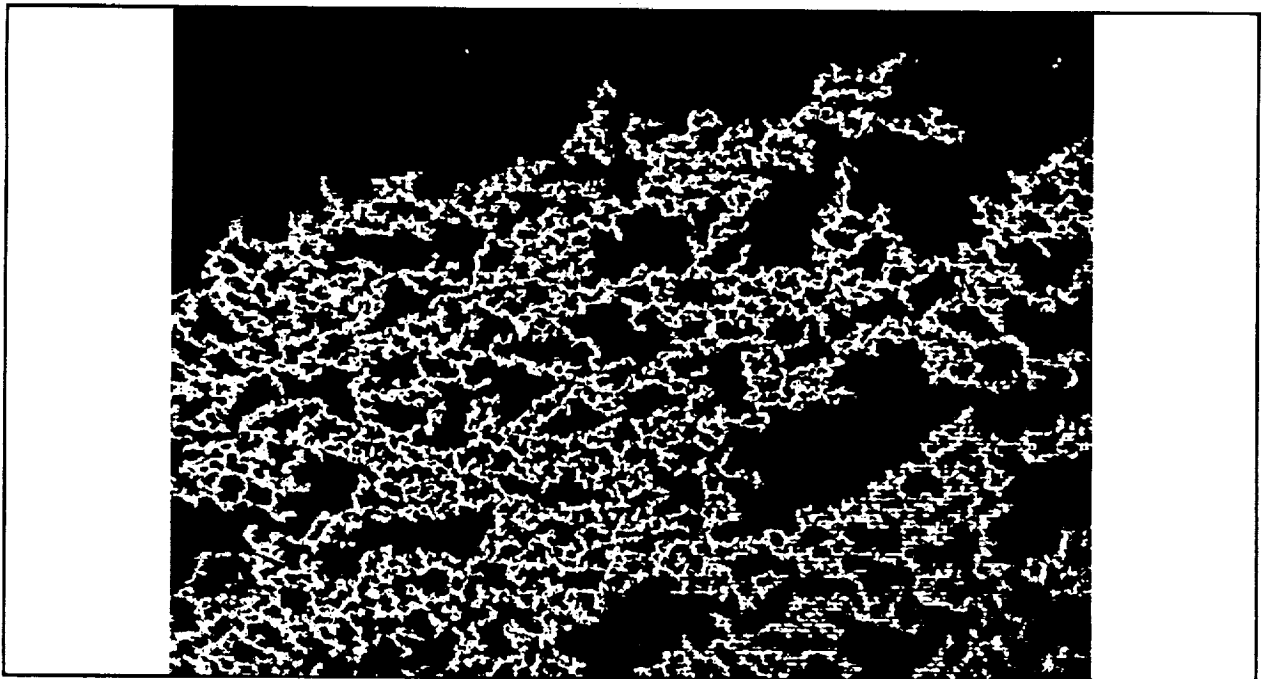
Figure 3b. Domain structure in S40ESiN sample developing at H=2.8 kOe.
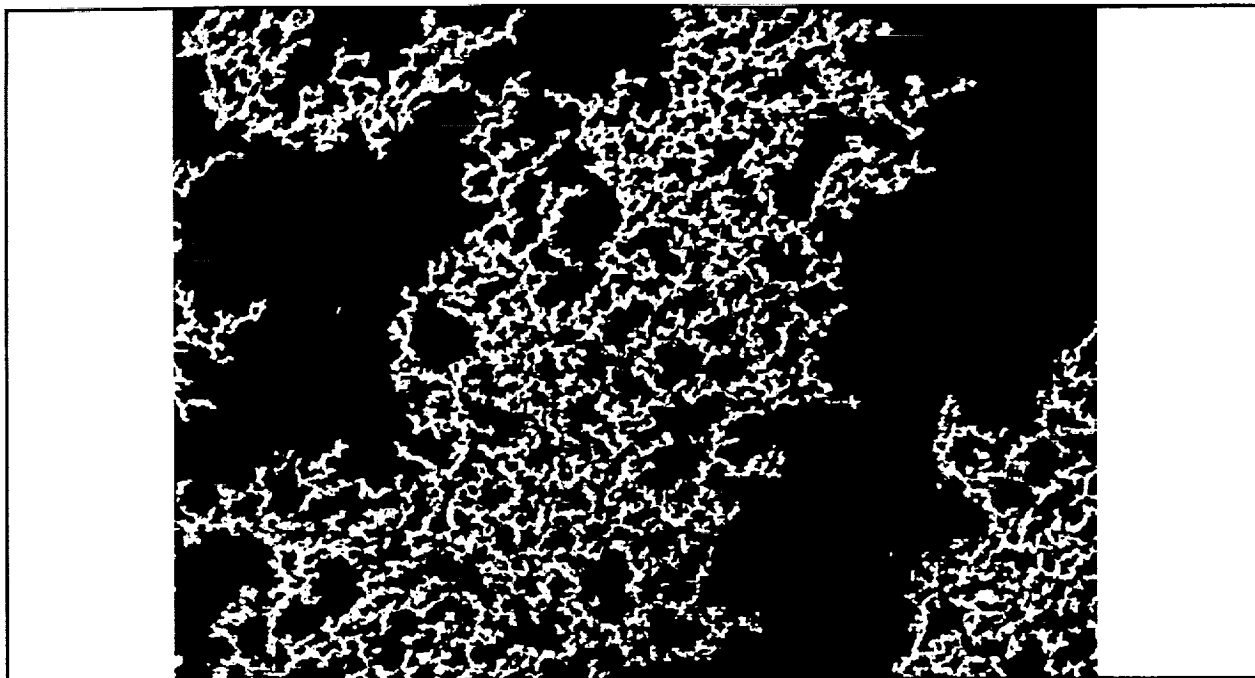
Figure 3c. Domain structure in S30ESiN sample developing at H=2.44 kOe.

⊢ 10μm ⊣
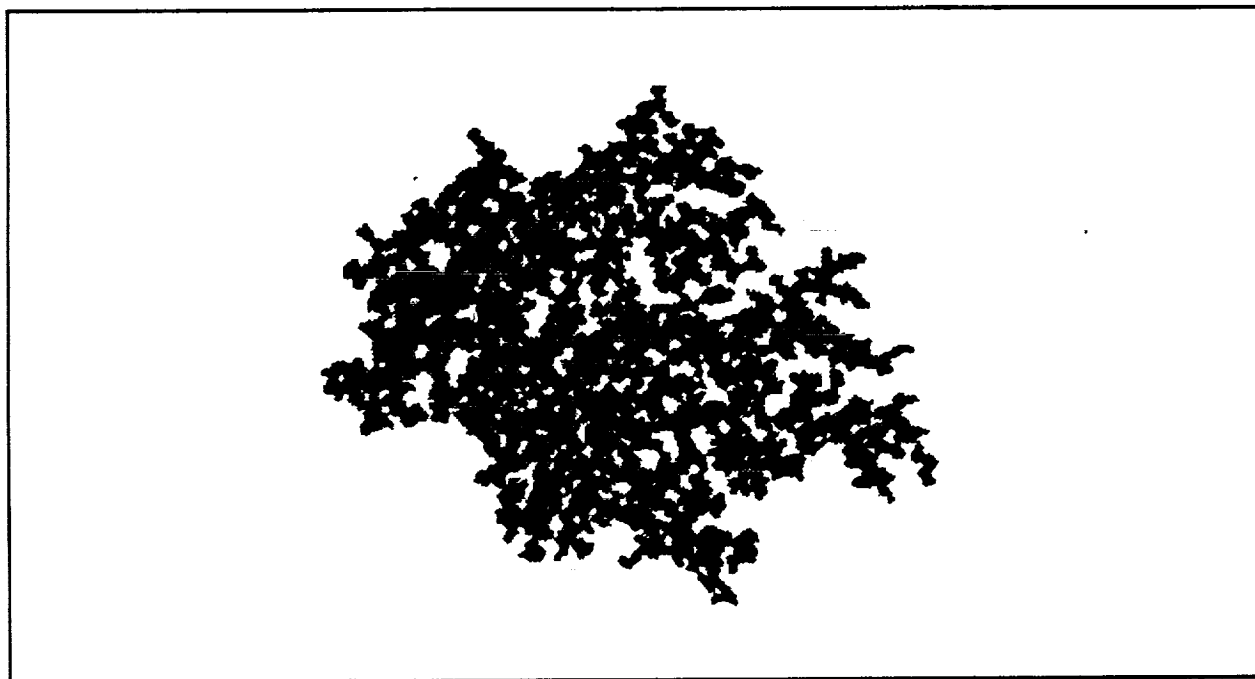
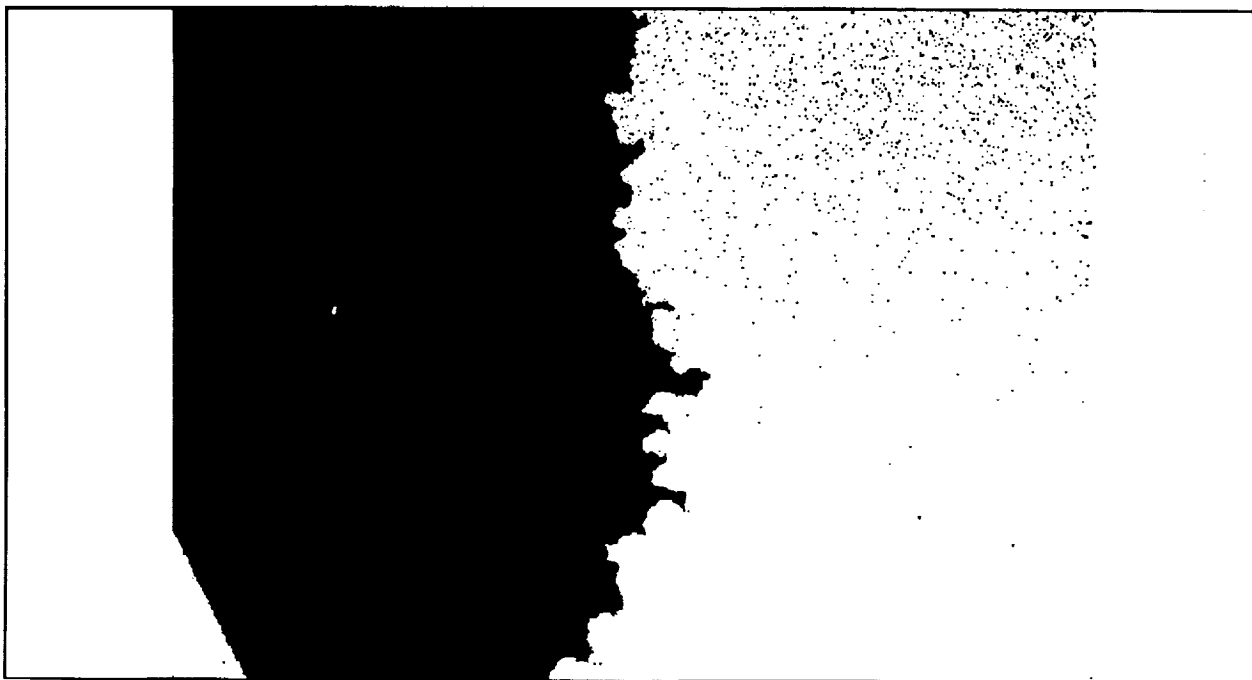**Figure 3d. Domain structure in S20ESiN sample developing at H=1.63 kOe.**
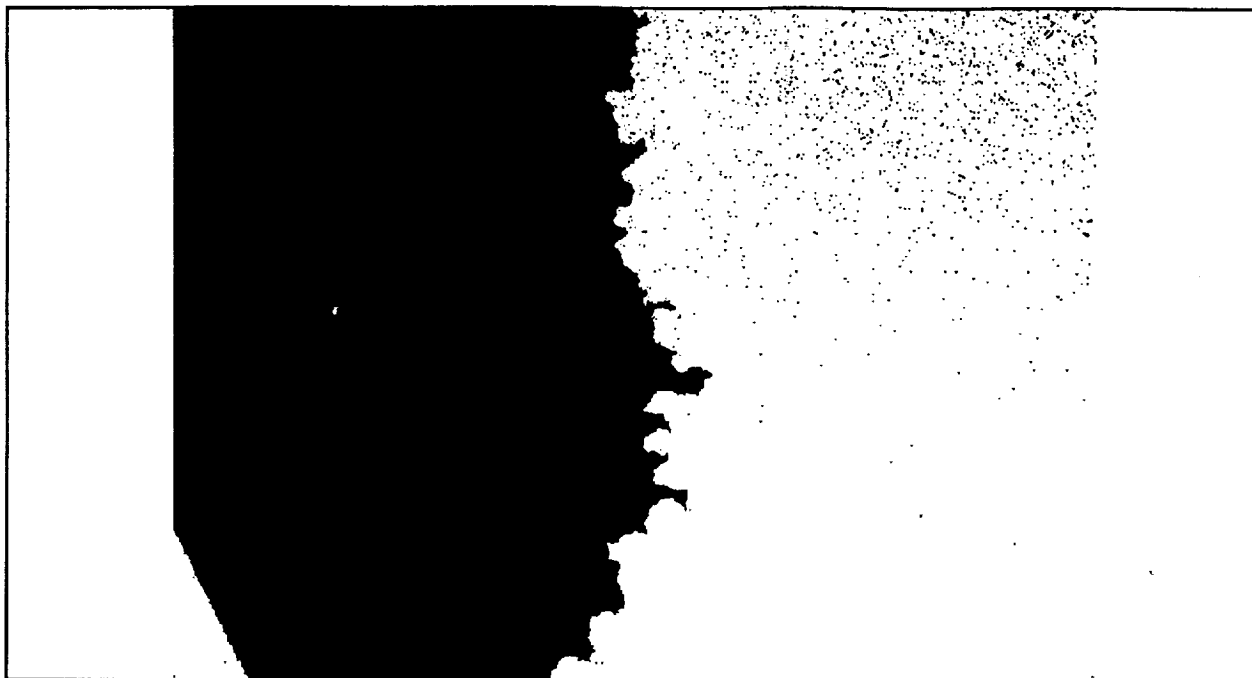
Figure 3e. Domain structure in S10ESiN sample developing at H=0.85 kOe.

⊢ 10μm ⊣
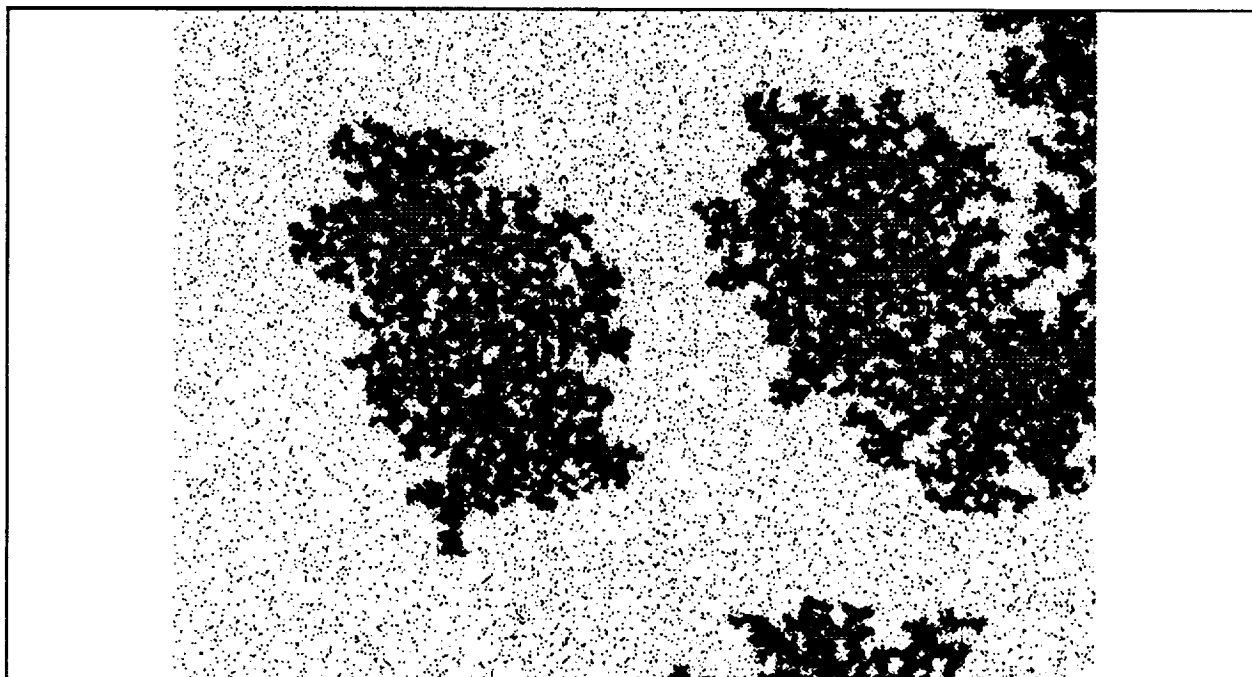
Figure 3f. Domain structure in S06ESiN sample developing at H=0.12 kOe.
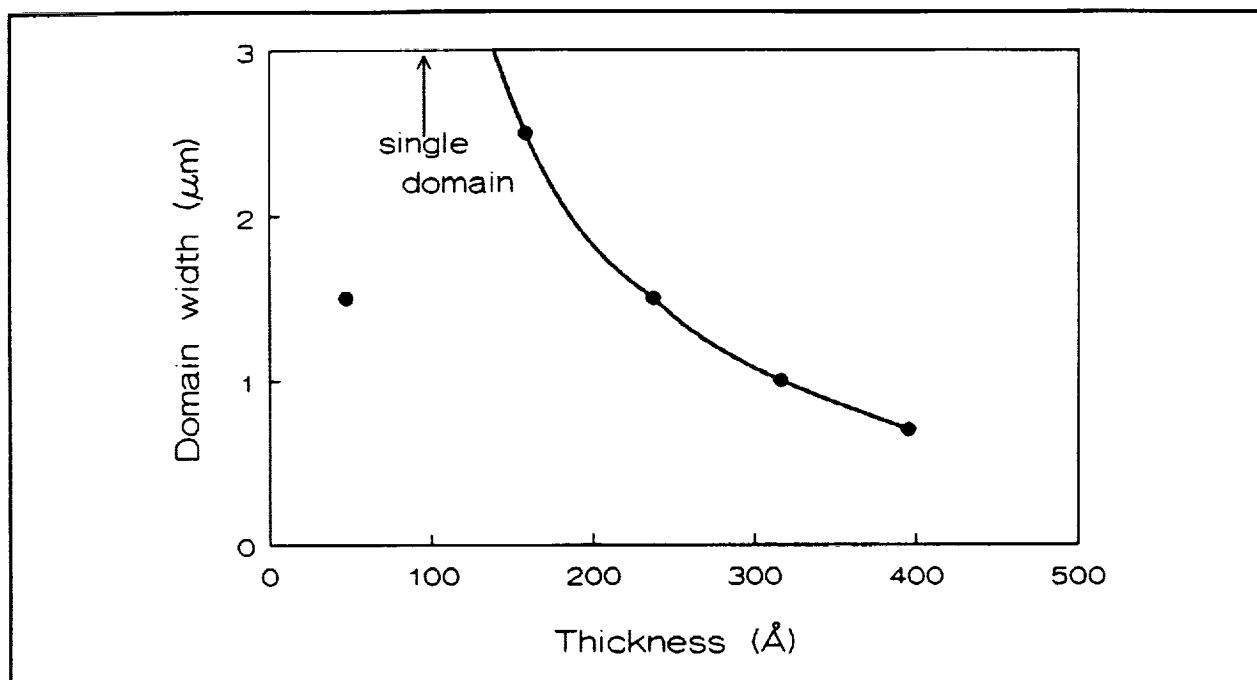
Figure 4. Dependence of average domain width on the thickness of Co/Pd multilayers.
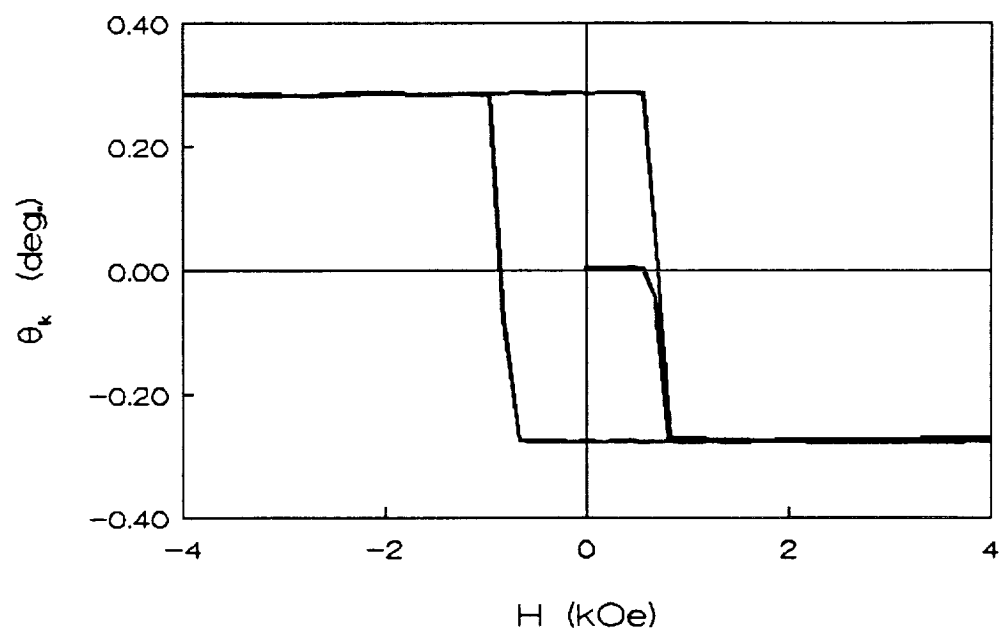
Figure 5a. Sample S10ESiN. Kerr rotation hysteresis loop and initial curve with perpendicular demagnetized field Hd= +580 Oe.
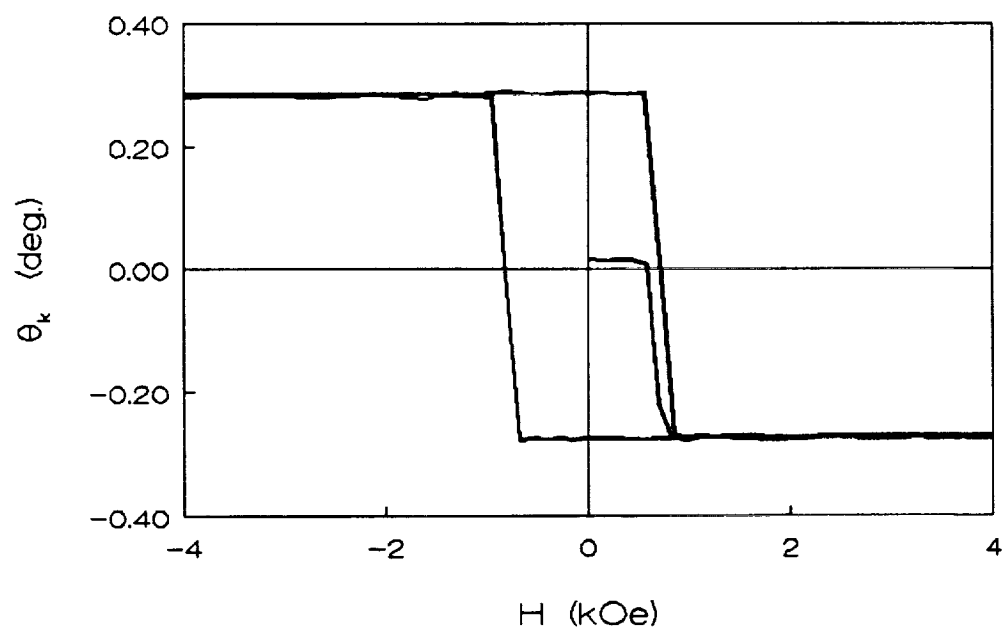
Figure 5b. Sample S10ESiN. Kerr rotation hysteresis loop and initial curve with perpendicular demagnetized field Hd=-620 Oe.
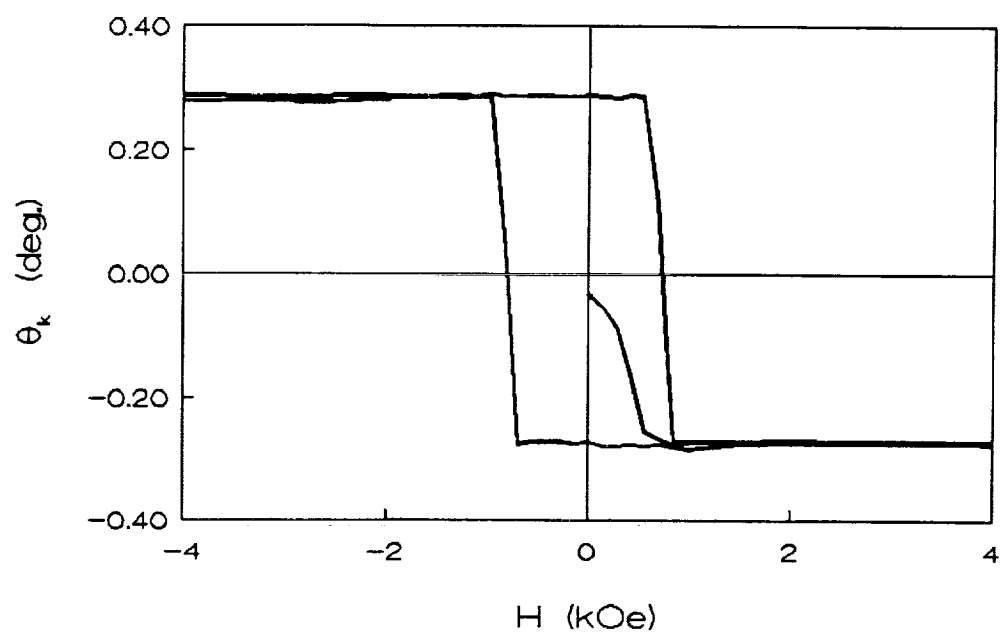
Figure 5c. Sample S10ESiN. Kerr rotation hysteresis loop and initial curve with in-plane demagnetized field.

Figure 6a. Domain structure in S10ESiN sample developing at H=0.85 kOe.

⊢ 10μm ⊣
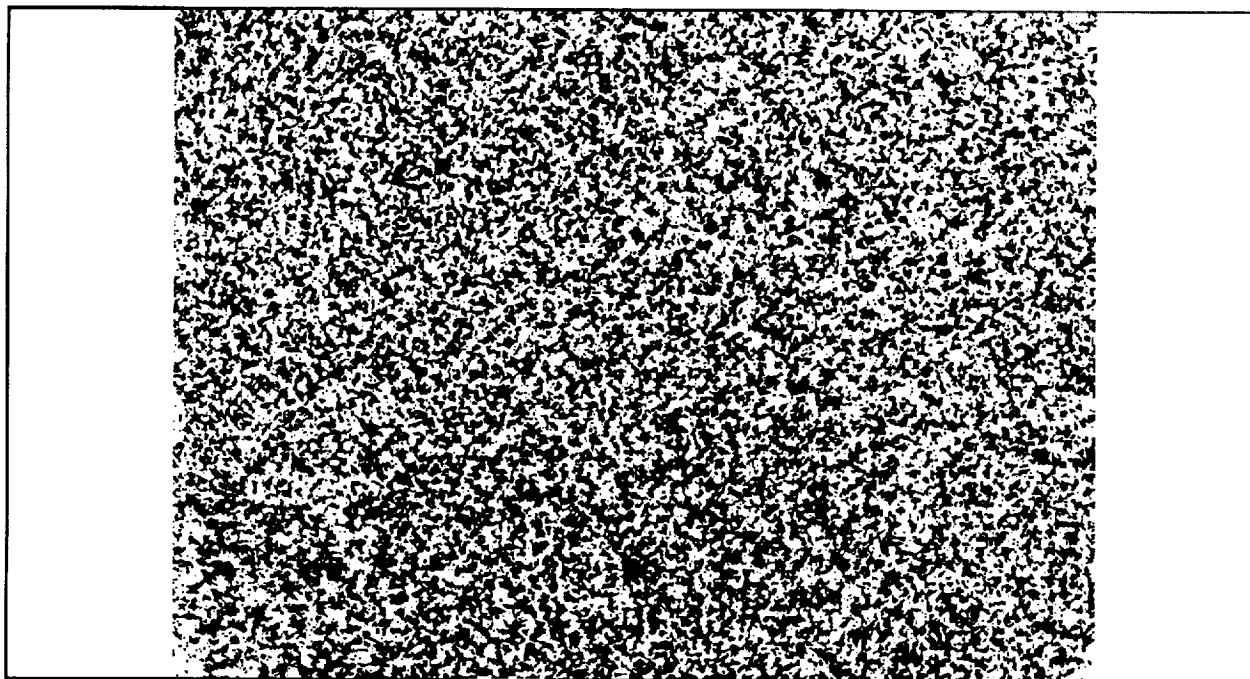
Figure 6b. Domain structure in S10ESiN sample after demagnetization by in-plane magnetic field Hd=20 kOe.
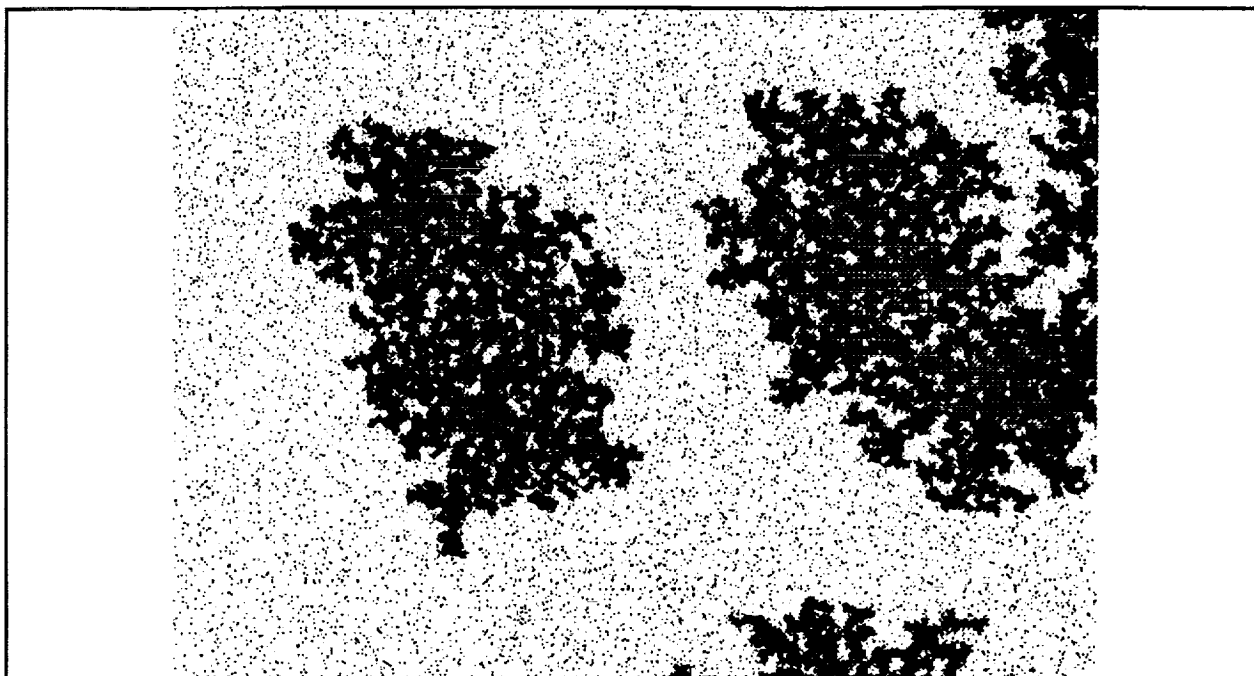
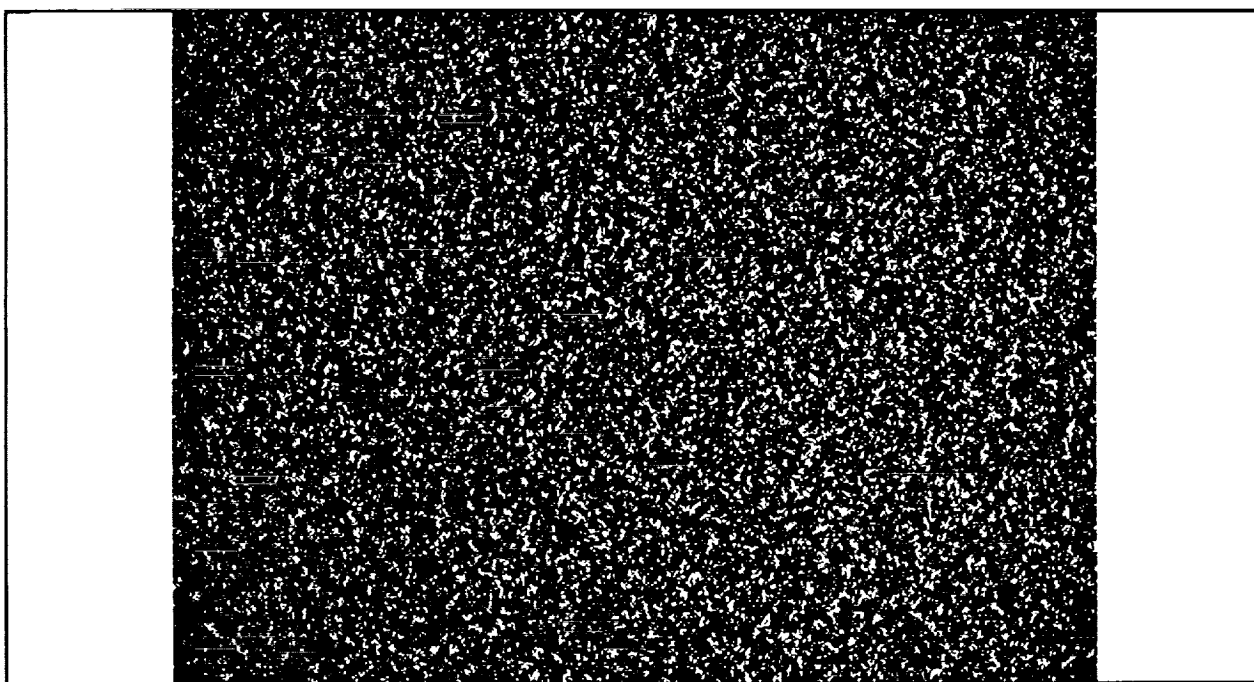Figure 6c. Domain structure in S06ESiN sample developing at H=0.12 kOe.

⊢ 10μm ⊣

Figure 6d. Domain structure in S06ESiN sample after demagnetization
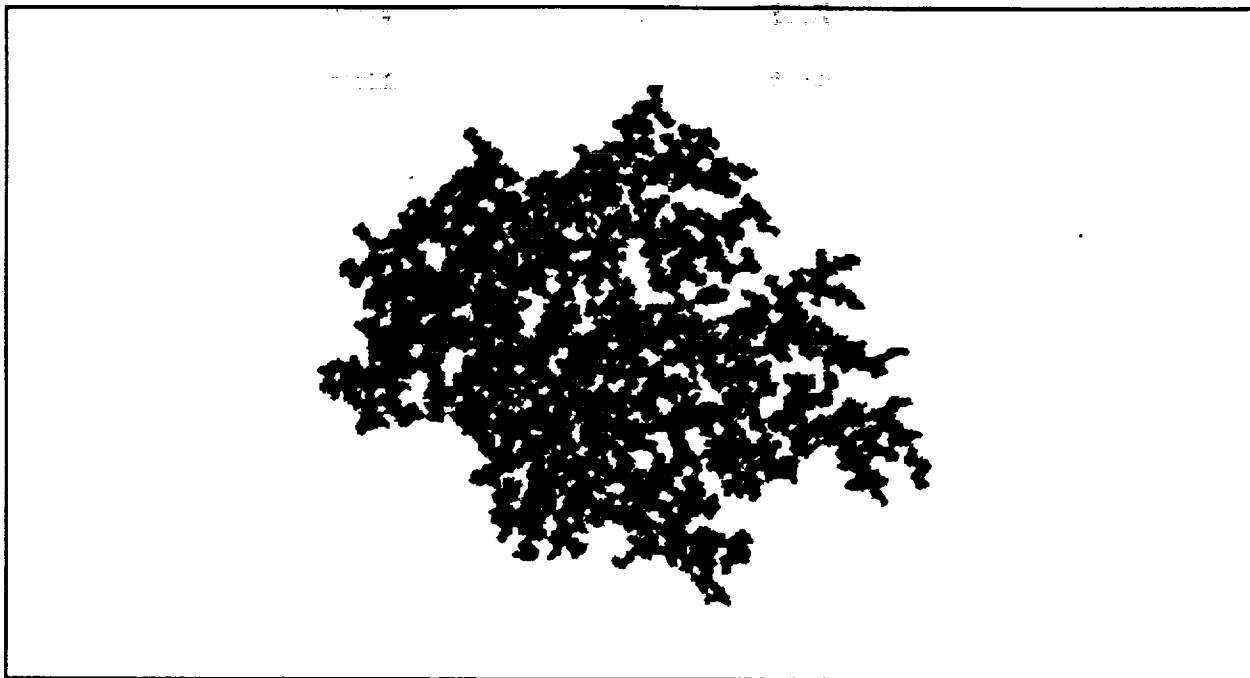by in-plane magnetic field Hd=20 kOe.

Figure 7a. Domain structure in S20ESiN sample developing at H=1.63 kOe.
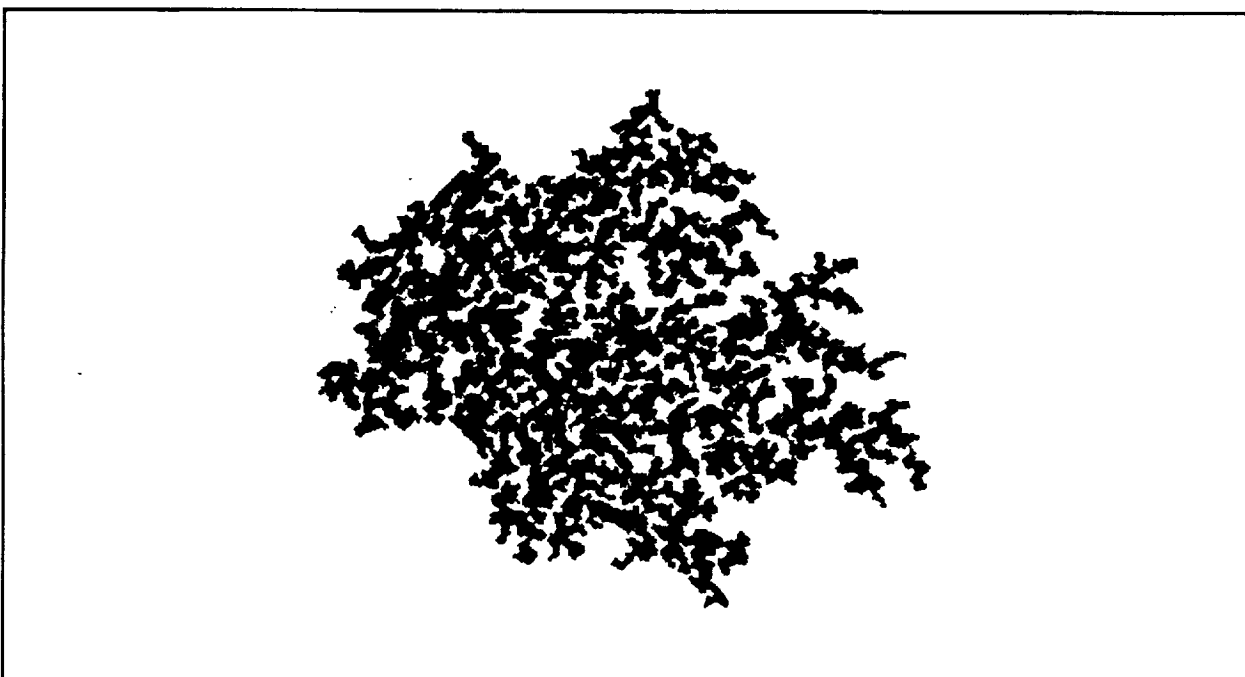
$\vdash 10\mu m \dashv$

Figure 7b. Domain structure in S20ESiN sample after application of reverse field. The initial domain structure is shown in figure 7a.
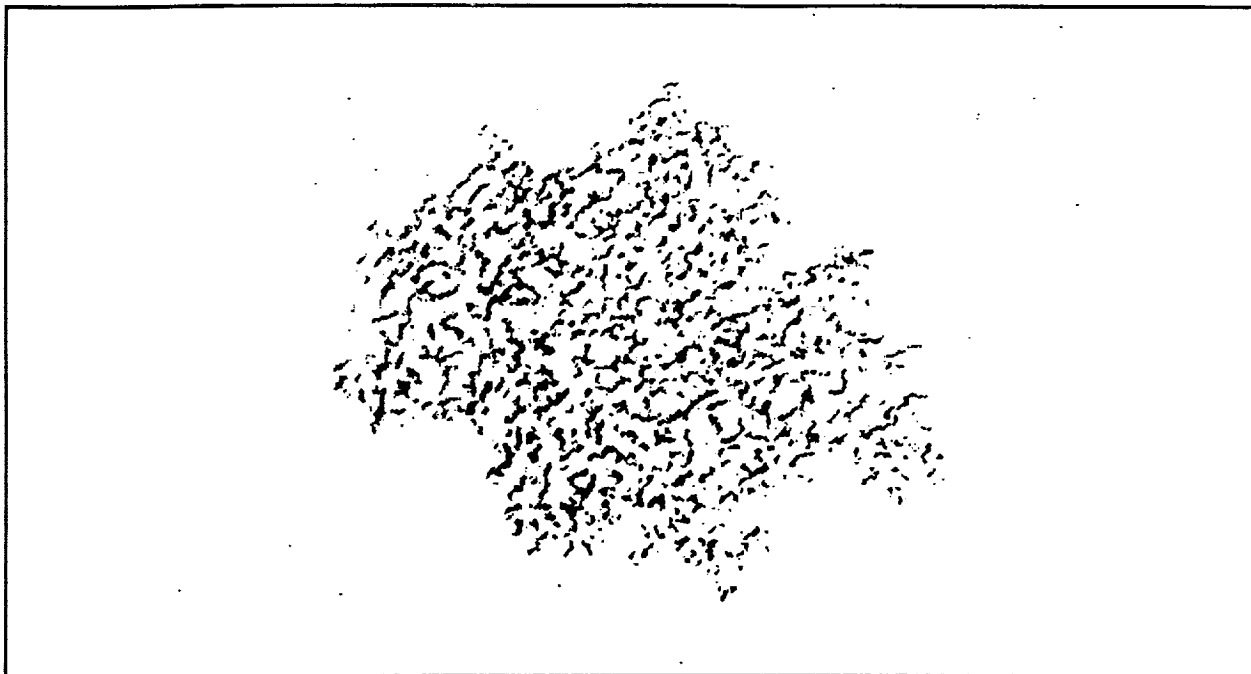
Figure 7c. The black areas show the difference between domain structures, shown in figures 7a and 7b.

$\vdash 10\mu m \dashv$

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APPENDIX D