FOLIS, A PC COMPATIBLE PHOTOLITHOGRAPHY SIMULATION TOOL

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Key words: photolithography, projection aligners, process simulation, microelectronics

Abstract: FOLIS, a relatively simple, PC compatible photolithography simulation tool, developed for photolithography process development and demonstration, is presented, and physical models incorporated into software outlined. Examples of simulations by FOLIS of selected photolithography process steps are given.

FOLIS, programsko orodje za simulacijo fotolitografskega procesa

Ključne besede: fotolitografija, projekcijski poravnalniki, simulacija procesov, mikroelektronika

Izvleček: V prispevku je predstavljen FOLIS, relativno preprost in za uporabo na osebnih računalnikih prilagojen programski paket za simulacijo in demonstracijo fotolitografskega procesa. Očrtani so fizikalni modeli, ki so vključeni v program in prikazani primeri simulacij izbranih faz v fotolitografkem postopku.

Introduction

Lithography is the cornerstone of modern IC manufacturing, and lithography tools and process characterization at the core of the lithography process engineering. A great majority of the ICs today are manufactured by optical photolithography. The concept behind it is relatively simple: a light sensitive photoresist is spun onto the wafer forming a thin layer on the surface, which is selectively exposed by light through a mask, containing the pattern of the particular layer to be patterned. The resist is then developed, which transfers the pattern on the mask to the wafer. The remaining resist is finally used as a mask e.g., to etch the underlying layer. As the dimensions of the features to be fabricated on the wafer approach 0.1 μm, the classical limit of the resolution of optical tools used in photolithography, the implementation of the simple concept becomes quite complex. In fact, complex enough for the tradition empirical tools of the IC manufacturing process development to be insufficient for the task at hand. They have to be complemented by different computer simulation tools which make understanding and optimization of the performance of the lithographic process possible. Such tools are based on the Fourier optics to describe the performance of exposure tools, and resist chemistry to describe the formation of the mask pattern in the resist. Photolithography simulation tools generally follow the directions developed by Dill /1, 2/, and a number of commercial products is available for simulation purposes. However, these tools themselves are quite complex and in connection with optimizing performance of the projection Ultrateh Stepper Aligner UTS 1100 in our Microelectronics laboratory, there was a need to develop a relatively simple, PC based simulation tool, which could also serve for demonstration purposes. The result of this efforts is FOLIS (FotoLItografski Simulator), a software simulation tool presented in this contribution.

Optical Considerations

All of the projection exposure systems used in IC manufacturing industry today are diffraction limited optical instruments. Consequently Frauenhofer diffraction theory (3) has to be incorporated in any simulation describing their performance. The basic tenet of the theory is that a point object is imaged by the optical system into a finite patch of light, or blur spot, in the image plain, i. e. the image of the source is not perfect. This obviously has important consequences for imaging the fine, detailed pattern present on the mask on the photoresist covered wafer. In FOLIS the imaging of the mask pattern is modeled by the standard Fourier analysis of the Frauenhofer diffraction. The diffraction theory is used to calculate spatial distribution of the light intensity I(r) in the blur spot, the image of an aperture in the mask. There is a small but significant difference between diffraction patterns of a circular and rectangular aperture. For the former, an axially symmetric spot (Airy disc), the intensity is given by:

$$I(r) = I_0 \left(\frac{2J_1(x)}{x} \right)^2$$

where $x = (\pi a \sin \Theta)/\lambda$, I_o the intensity maximum in the center of the disk, a the diameter of the aperture in the mask, Θ angle between the direction of the intensity maximum and direction of the current position in the image, λ the wavelength of the light, and J_1 the first order Bessel function. The expression for rectangular aperture is analogous and results of a FOLIS simulations for both are shown in Fig. 1. According to the Rayleigh criterion the maximum resolution R of the projection optics can be extracted from the above expression:

$$R = 1.22\,\lambda/\,NA,$$

where NA is the numerical aperture of the projection system. This expression strictly applies to point sources only. In real photolithographic systems, imaging a variety of shapes of finite dimensions on resists of different abilities to distinguish closely spaced features, further details of the imaging, e.g. defocusing of the image plane, have to be considered. Usually all such effects are incorporated into a factor k_{LW} in the corrected expression for R, i.e. the minimal line width that can be imaged:

$$R = k_{LW}\lambda/\,NA$$

In practice k_{LW} is a number between 0.8 and 1.0, resulting in e.g. 0.36 μm resolution for the Hg emission I line in the UTS 1100 aligner. As this projection aligner utilizes I, H, and G emission lines, all 3 are considered in the FOLIS simulations.

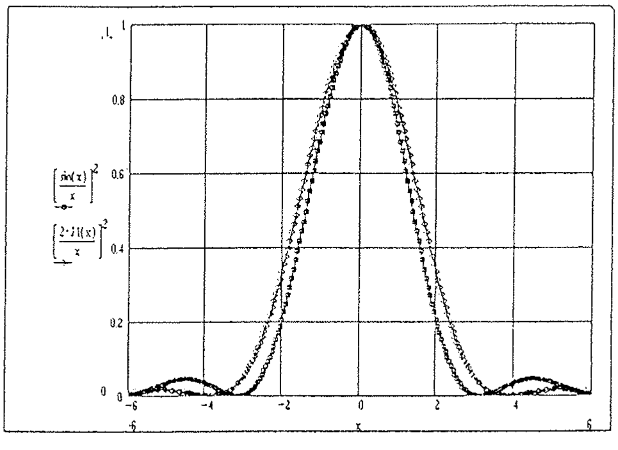

Fig. 1: Airy disk simulaton by FOLIS for circular point source (diamonds) and line source (squares). x—axis divisions are scaled by the objective focal length.

Depth of focus (DOF) of the imaging optics also influences the resolution limit and is considered in FOLIS. The Rayleigh criterium for the DOF is simply translated to the requirement that the lengths of the on-axis and edge of entrance aperture rays not differ by more than $\lambda/4$, and

$$DOF = k_1\,\lambda/(NA)^2$$

where k_1 is a factor analogous to k_{LW}, accounting for the increased DOF for larger features, the dependence of DOF on other factors, e.g. resist process.

Another basic optical concept allowing modeling of the aerial image on the surface of the photoresist film, which is incorporated into the FOLIS, is the modulation transfer function (MTF) /3/. MTF is basically a measure of the contrast in the aerial image produced by the exposure system. It is defined as

$$MTF = \frac{I_{maax} - I_{min}}{I_{max} + I_{min}}$$

where I is the intensity of light at different parts of the image. MTF of a system depends on a variety of factors, including the illumination light wavelength, mask spatial frequency and feature size to be transferred to the photopolymer, the NA of the lens, and spatial coherence of the source. MTF decreases with the mask feature size and is at the resolution limit for an ideal mask only 0.5. Generally, an exposure system needs to achieve a MTF value of at least 0.5 in order for the resist to properly resolve the features incorporated in the mask. In principle the concept of MTF strictly applies only to coherent illumination, however, its approximations for partially coherent radiation are known /4/ and this is incorporated into the FOLIS. The aberrations of the Wynne—Dyson imaging system of the UTS 1100 are neglected in our simulator, and DOF treated as a phase aberration. In Fig. 2 an example of the Bosung plot calculated for a diffraction grating-like mask of 0.6 μm line width and 1.2 μm pitch is shown. It should be noted that in practice actual measurements of such data are quite difficult and therefore an accurate modeling of the image of great value.

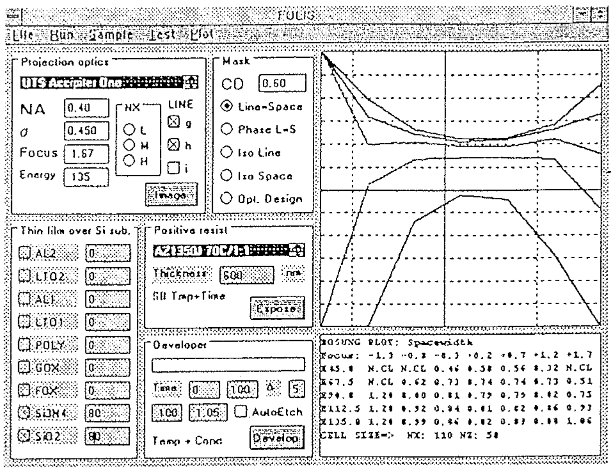

Fig. 2: Bosung plot (UTS 1100 projection stepper and 600 nm AZ1350J photoresist on SN-SO covered wafer) for a 0.6 μm CD line-space mask structure, calculated by FOLIS.

Photoresist Image

Formation of the aerial image, and its quality, by the exposure tool is the first step of the photolithographic process that is considered in modeling. Translation of this image into its 3 dimensional replica in the photoresist is the next one. Geometric accuracy, exposure speed, and also patterned resist physical and chemical properties have to be considered. While the later aspects of this stage of processing are not modeled by the FOLIS at this time, the first two are.

There are several reasons for the optical intensity pattern of the aerial image to be different from the intensity pattern in the resist layer. One is the reflection of light from underlying structures which results in establishing a 3 dimensional standing wave pattern in the resist, resulting in an exposure pattern that reflects it. Modeling of the standing waves is relatively simple only if it is assumed that the light entering the film is all vertically incident, i.e. parallel rays perpendicular to the wafer plane, and this is the approximation used in the FOLIS. In an exposure systems with a high NA this is clearly not the case. Partial coherency of the light source and the reflected light further complicate the calculations as they involve an integration of effects over the total angle of the incoming light. Non-uniform resist film thickness and similar factors of random nature are not considered.

The calculation of the standing wave pattern in the resist layer is a straightforward application of the electromagnetic theory /3,5/ - electric field at different depths in the film is calculated, taking into account the change in wavelength of the light in the photoresist film due to its refractive index, reflection coefficients at interfaces and absorption coefficient of the film. In FOLIS this is accomplished by the standard technique of introducing the complex refractive index. The light intensity is then simply proportional to the square of the magnitude of the electric field. In Fig 3. a simulation of the standing wave pattern in a uniform photoresist film of 0.65 μm thickness on bare Si substrate, for the 3 wavelengths used in the UTS 1100 projection aligner, is shown. The actual calculation of the standing wave pattern in a more realistic structure, e.g. oxide layer in top of Si, or several films, each with different optical properties, is considerably more complex, but is approached in an analogous manner as the simplest case.

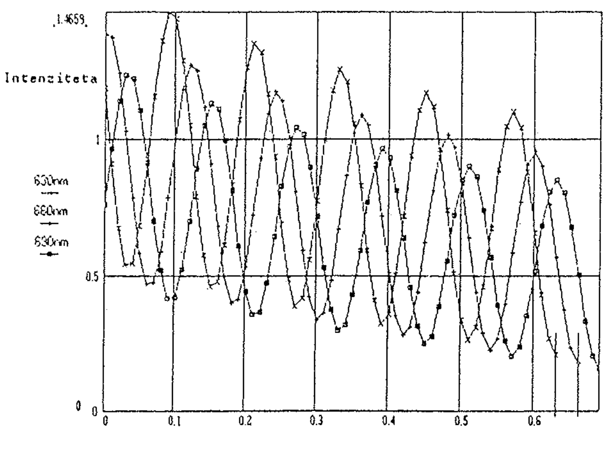

Fig. 3: Standing wave pattern in a 0.65 μm photoresist layer for G, H, and I Hg emission lines, as simulated by FOLIS. Intensity units are arbitrary.

The light intensity in the photoresist film, calculated as described above, is not directly related to the transfer of the aerial image on the film surface into the 3D image structure in the exposed film. During the exposure the optical properties of the resist material change with exposure time (the so called resist bleaching). The effect can be handled by the Dill model of the positive photopolymer /6, for a review see 2/. In this model the film is treated, essentially, as a succession of a number of thinner layers, each thin enough for the bleaching effects to be considered uniform throughout the film subdivision, and certainly thinner than $\lambda/2n$ (where n is the refractive index of the photopolymer material), the spatial frequency of the standing wave pattern in the resist film. The changes in the exposed photoresist are related to the changes of concentrations of one of its components, e.g. the inhibitor, and local bleaching rate calculated from the concentrations and light intensity at a point. The model involves determining 3 parameters (Dill parameters) for the resist and iteratively solving 2 coupled equations, simultaneously with the equation of the standing wave pattern. The results of the procedure in FOLIS, for 1 μm film of the AZ1350J resist on 3 different underlying structures, exposed in UTS1100 projection aligner at 50 mW/cm^2, is shown on Fig. 4. Only G and H Hg emission lines are included in the calculation. As most modern exposure tools use monochromatic light, such effects are even more pronounced, and consequently the control of critical dimensions in the exposed resist film even more difficult.

Photoresist Developing

Photoresist developing is a surface controlled etching process /6/. In modeling it is assumed, that at each point the developer solution etches the surface of the resist isotropically, with the etch rate at each point governed by the local concentration of the resist inhibitor. Of course, it is exactly the local (normalized) concentration of the inhibitor that is calculated by the exposure model described above. The dependence of the etch rate on the inhibitor concentration is nonlinear. In FOLIS, as in most models, terms higher than quadratic are neglected. Time evolution of the developing resist profile is calculated by setting up a 2 dimensional grid, where the inhibitor concentration is defined in each cell, and the developer moving into the resist at local etch rate, thereby evolving the profile. 2 different methods for calculating the evolving pattern are used in FOLIS. One is an interactive cell method that is computationally relatively simple. An example of calculating the developed profile in 0.5 μm AZ1350J resist film by the interactive cell method is shown on Fig. 4. The relatively large size of the cells has been chosen for clarity. The 2 dimensional interactive cell method can easily be extended to 3 dimensions, and an extension of FOLIS in this direction is considered.

The second method for calculating the resist profile in FOLIS is the advancing front method. In this case the lat-

$M=1$

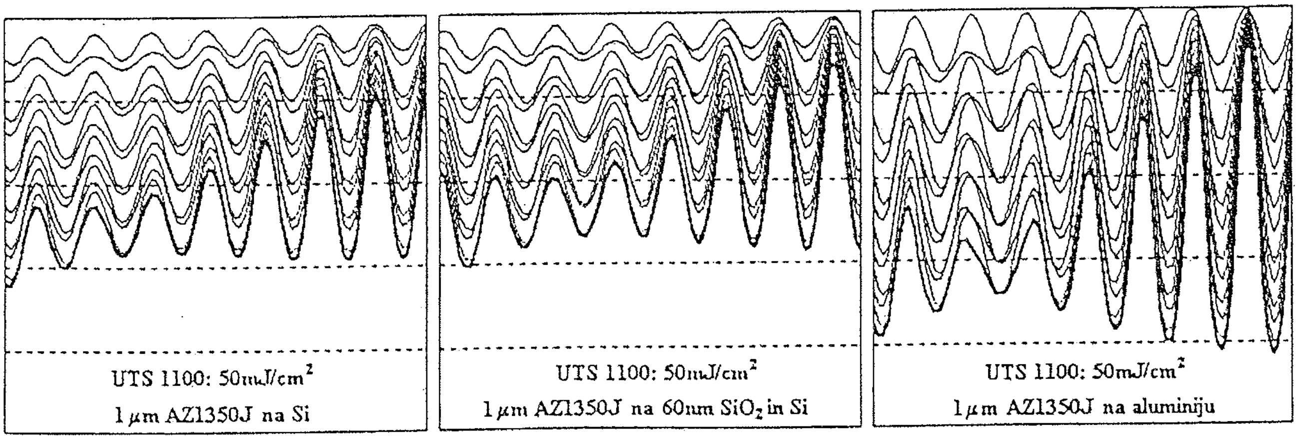

Fig. 4: Time evolution of inhibitor concetration M in photeresist on different substrates (Si, 60 nm SO on Si, and aluminum), as simulated by FOLIS.

tice points define, locally, the interface between the resist and developer and this interface (front) advances into the resist, according to the local etch rate. Such a computation process is easy to relate to the evolving resist profile, however, it is computationally quite demanding and slow. An example of developed 1.5 μm AZ1350J resist film, as calculated by this method, is shown on Fig. 5 and Fig. 6.

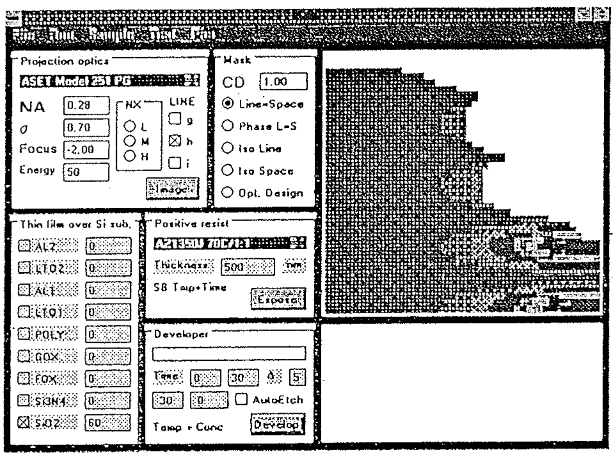

Fig. 5: Photoresist development simulation (interactive cell method) by FOLIS.

Phase Masks

Efforts to improve the resolution of lithography systems are directed not only towards improving the exposure tools and photoresist processing, but also to designing masks with advanced features that allow better transfer of the design pattern to the photoresist. For the projection lithography tools phase masks are of considerable interest and it thus seemed desirable to include, for demonstration purposes, at least some of the features of phase mask operation into the FOLIS. The concept of phase shift masking techniques is not new and has been proposed some time ago /7/, however, its application to the masking process prooved to be quite complex. The concept is based on the elementary fact, that any diffraction pattern observed in the aerial image plane is a result of superposition of electric fields of the light waves scattered by the mask. Diffraction minima in the image are the sites where the fields cancel, and conversely maxima the sites where they add constructively. At an image point the phases of the light waves, arriving from different positions of a standard e.g. chrome "black and white" mask, are determined solely by the different geometrical path lengths from the point to the different positions on the mask. The result of superposition, e.g. for a circular opening in the mask, is the familiar Airy disk pattern of the image. However, the phase of light waves emerging from the mask can also be altered by adding to the mask the so called phase shifters, which are basically transparent films of appropriate thickness and index of refraction. For a 180 deg. phase shift the relation between the thickness d, refractive index n and the wavelength of the light λ is

$$d = \lambda/2(n - 1)$$

By suitable positioning of the phase shift plates on the mask it is possible to arrange for the electric fields at desired sites in the image to be canceled. The photoresist responds to the intensity of the light, which is proportional to the square of the electric field and is thus not effected directly by the phase of the light waves. But by causing the fields to cancel at desired image sites, the resolution and quality of the aerial image can be significantly improved (2,7).

It is not excessively difficult to calculate, by the Fourier methods, the light intensities in the image plane for phase masks with relatively simple geometries. Fig. 7. illustrates a FOLIS simulation for a via mask in which the geometry of the contact via is represented by an opening in the chrome,

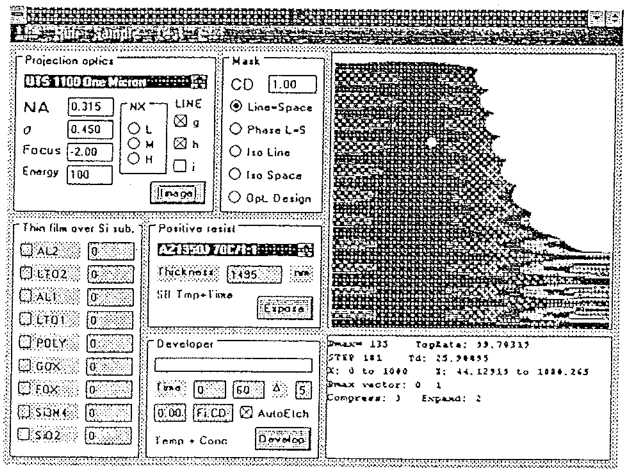

Fig. 6: Photoresist development simulation (advancing front method) by FOLIS.

i.e. dark field, (a), chrome patch (light field, b), 180 deg. phase shift plate with dimensions of the via on light field (c), and 180 deg. phase shift plate behind in an opening (dark field + phase shift, d). Top part of the figure represents the (normalized) electric field intensities immediately behind the mask, and the lower part the light intensities in the image plain. (It should be noted, that the simulation includes a mirroring of the image around the optical axis by the objective lens.) Clearly the contrast afforded by the phase shift mask (b) is largest, exceeding contrasts of other mask types by at least a factor of 2. A simulation of a mask of greater complexity is shown on Fig. 8. As in Fig. 7, on the top the electric field intensity behind the mask is shown, light intensity in the image plain for a phase mask (center), and the light intensity for the same mask geometry without phase shifting (bottom). It can be observed that imaging of the phase mask retains greater detail of the mask geometry than is the case with standard mask, however, the image is distorted. At present FOLIS is incapable of simulating and optimizing image light intensities for a masks with random pattern geometry, which would, presumably, model a real life mask more closely.

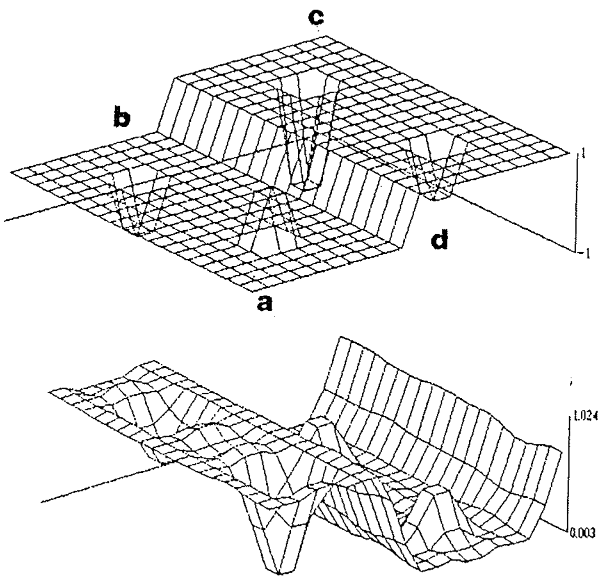

Fig. 7: Via imaging by different masks: (a) dark field, (b) light field, (c) 180 deg. phase shift plate with dimensions of the via on light field, (d) dark field + phase shift, as simulated by FOLIS.

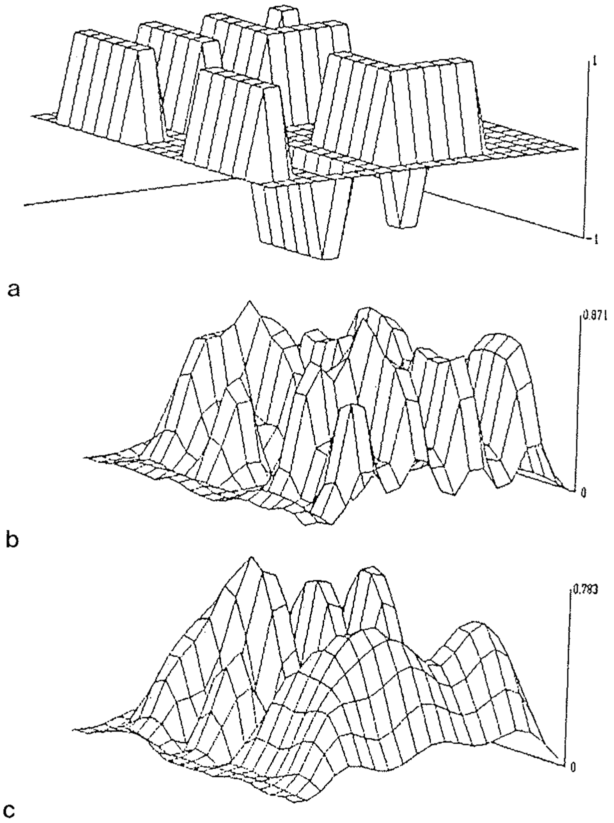

Fig. 8: Via imaging for a »random« phase mask. (a) electric field behind the mask, (b) aerial image at focal plane, (c) image of standard mask of same geometry, as simulated by FOLIS.

Conclusion

The FOLIS simulation tool has been developed to augment the introduction of projection alignment techniques into the Microelectronics Laboratory of the Faculty of Electrical Eng., University of Ljubljana. An important development goal has been to provide a means of demonstrating the relatively complex photolithographic topics and process to the faculty students. At present the FOLIS program package is not being further developed but improvements, indicated in the text, are planned for the future.

Acknowledgements

Part of the FOLIS development work has been performed as partial fulfillment of requirements for an M. Sc. degree of the first author. The work has been supported by a grant from the Ministry of Education, Science, and Sports of the Republic of Slovenia. The use of IMP (San Jose, Ca., USA) facilities for some of the work presented is gratefully acknowledged.

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Prispelo (Arrived): 21.06.2002 Sprejeto (Accepted): 25.03.2003