Chapter 4
Cleaning and Cleanliness

4.1 INTRODUCTION

As used in this chapter, *cleaning* refers to removing undesired material from the wafer before subsequent process steps (some of this undesired material may be remnants of materials used in previous processing steps). *Cleanliness* refers to preventing contamination, and to maintaining the level of cleanliness already present. Environmental and handling considerations (Section 4.2) address cleanliness.

Cleanliness is crucial to achieving high yields and reproducible processes in the production of any semiconductor device. The effect of particles in causing defects is obvious. Less apparent, but even more insidious, is the effect of "minor" chemical contamination or poor environmental control. These can degrade or destroy virtually any aspect of the fabrication process. Metal adhesion, resist application and patterning, wet etching, dry etching, and plating are only a few examples. The semiconductor industry is full of "horror stories" of process lots ruined by some subtle departure from purity. In such cases, availability of the diagnostic techniques described in Chapter 19 can be enormously useful in aiding a rapid diagnosis of the problem.

"Clean" is a relative term. No surface or chemical is completely pure in the real world. We shall adopt the common sense approach of defining "clean" as being clean enough to result in a reliable, reproducible procedure for the particular process step in question. This standard can be rather stringent. A few monolayers of a constaminant can radically alter metal adhesion. Fortunately, most chemicals and gases can be reliably obtained in a high purity form because of the historical need of the silicon industry. Many chemicals are precisely intended for such use and are designated "semiconductor grade." Nevertheless, to obtain a "bad" lot is still possible. Initial purity is only part of the battle. Good etiquette must be rigorously observed to prevent subsequent contamination. Minor traces of contaminants on beakers, stirring rods, thermometers, tweezers, wafer holders, or other items can degrade the purity of the chemicals.

Early research work in GaAs did not demand high cleanliness standards. Device area was small and only a few "good" devices were needed for research projects. However, any significant production of semiconductor devices places a high premium on uniformity (both across a wafer and wafer-to-wafer) and yield. Uniformity, of course, is one requirement for high yield. Demand for GaAs products (Chapter 1), especially MMICs, requires that thousands to millions of integrated circuits be produced with nearly identical operating characteristics. Uniformity in performance follows directly from uniformity in material and process.

Yield is tied to cost, and affordable products demand high yield. GaAs analog microwave devices and integrated circuits have relatively few gates (the smallest geometry portion of the device) by silicon standards, but GaAs digital logic circuits employ thousands of gates, and hence begin to face the same challenge faced by silicon integrated circuits: one bad gate out of thousands can ruin the entire circuit. Hence, elimination of particles is increasingly important as the number of gates increases. Particles on the wafer can cause pattern defects, resulting in electrical failures such as short circuits in capacitors or open circuits in gate fingers. Particles that cause openings in dielectric films can result in reliability problems. Particles that become included in resist films interfere with proper thickness uniformity and exposure. Particles can also damage masks used in contact photolithography. Resist operations in general must be free from particle contamination.

If defects are randomly distributed over the wafer, as is the case for particles falling on the surface of the wafer from the environment, the yield is given by a Poisson distribution, the usual formula being

$$Y = e^{-DA_c}$$

where Y is the yield, D is the defect density, and A_c is the critical or active area of the wafer. The critical area is the portion of the wafer in which defects cause device failures. The source-drain space of FETs is one example. Note that the critical area will generally be much smaller than the total area of the wafer. This formula pessimistically predicts yield to fall exponentially with increased active area. However, total defects may not be uniformly distributed over a slice (crystal defects, for example), and this consideration has led to a more optimistic formula that is widely used in the silicon industry [1]:

$$Y = \int_0^\infty f(D)e^{-(DA_c)}dD$$

where $f(D)$ is a probability density function giving the defect density distribution. A number of distribution functions have been used in this model, including an exponential distribution that gives [2]

$$Y = 1/(1 + DA_c)$$

There are arguments that these modifications are too optimistic [3]. These distinctions, however, are most pertinent for VLSI (*very large scale integration*) geometries employing tens of thousands of gates, a case not relevant to analog GaAs devices. For discrete devices, and MMICs especially, the basic Poisson approach is a good rule of thumb.

A great many of the cleaning and cleanliness techniques developed in the silicon semiconductor industry can be applied directly to GaAs fabrication. Of course, the differences in the two types of devices (silicon-based, and GaAs-based) lead to different sensitivities to various contaminants.

4.2 ENVIRONMENT AND HANDLING (CLEANLINESS)

Cleanliness is preserved by good environmental and wafer handling techniques. These include control of the number and size of particles present in the fabrication area, the temperature, and the humidity. Wafer handling techniques are particularly important given the propensity of GaAs to cleave or shatter under mild stress. The cleanliness standards require that most fabrication occur in environmentally controlled areas called *clean rooms*. These rooms generally use only yellow light so that resist may be handled freely (photoresist is not sensitive to yellow light; ordinary room light will expose it before it can be used). Appropriate yellow filters are placed over light fixtures, windows, and microscope lights. Because of this feature, clean rooms are sometimes known as *yellow rooms*.

4.2.1 Particles

Clean rooms are categorized by the number of particles contained in the air. This is given by the *class*. *Class-X* means that a cubic foot of air contains less than X particles that are $0.5~\mu m$ or greater in diameter. Thus, a class-100 clean room has one hundred or less such particles in a cubic foot of air. The general environment in an average building usually exceeds class-100,000. (The amount of debris present in ordinary rooms was impressed on the author when he once unpacked and uncovered a clean, six-inch telescopic mirror. It was impressive to hold the mirror and see particles visibly begin to cover its surface over a period of only tens of seconds.) Class-10,000 is relatively easy to obtain and can be used for some assembly or probe operations. However, serious fabrication efforts usually occur in environments near class-100, even class-10 (advanced silicon areas are moving to class-1, which generally precludes the presence of humans, regardless of how well they are garbed). Class-100 requires good filtering techniques and protective clothing on personnel. The present nomenclature is based on $0.5~\mu m$ particles, although there continues to

be considerable discussion of the merits of adopting particles $0.125 \ \mu m$ in diameter as the standard. There are commercial machines that measure the particle count, which may vary greatly as a function of location within the clean room and with surrounding activity. Assuming that there is decent filtering of incoming air, the major source of particles is personnel. Table 4.1 gives typical examples of the increase in particle contamination caused by various personnel activities [4]. Of course, the exact results are complex and depend on many factors, and so the table should be taken as indicative only. The major procedures used to reduce particle contamination within the general environment are to filter all incoming air and to clothe personnel in protective garb.

Table 4.1
Typical Particle Increases Caused by Personnel
$(0.2 \ to \ 50 \ \mu m \ particles; \ from \ [4])$

Activity	Times Increase Over Ambient
Normal walking	1.2 to 2
Sitting quietly	1 to 1.2
Gather 4 or 5 people at one location	1.5 to 3
Normal breathing	1
Breathing of smoker (up to 20 min after smoking)	2 to 5
Sneezing	5 to 20
Rubbing skin on hands and face	1 to 2
Laminar flow work station (with hands inside)	1.01
Brushing sleeve (protective clothing)	1.5 to 3
Removing handkerchief from pocket	3 to 10

Filtering may be done in several ways. The most effective (and most expensive) is to force air through filters placed continuously on the ceiling and extract the air through perforated flooring. Adjustable dampers may be placed in the floor segments so that the room can be "balanced" to provide vertical laminar flow at equal rates across the entire area. This type of installation is expensive because of the large filter area and the special ceiling and raised floor that must be constructed. A less expensive technique is to place a bank of filters in one wall and extract air at the other end of the room. The area nearest the filters will be the cleanest. However, good air flow may be impeded by equipment or personnel within the room. All such filtering techniques require rather substantial "blowers" to force air through the filters. Air flow should be sufficient to make the room "positive pressure," so that when

doors are opened, air flows out instead of in. This prevents particles and moisture from being brought in from the outside. The air that is extracted (through the floors or walls) is recirculated through the filters. However, a significant fraction of the room air may be removed as "exhaust air" from such items as chemical fume hoods. These may draw air at approximately 100 SCFM (*standard cubic feet per minute*) for every linear foot of length. Such exhaust is clearly unsuitable for recirculation and must be replaced by "make-up air" from the outside.

Protective clothing for personnel may include smocks, hoods, face covers, gloves, safety glasses, and booties (to slip over shoes). Pads of sticky sheets may be placed near entrance areas to remove loose dirt from shoe bottoms. The pads are located so that personnel naturally walk across them when entering the "smock-up" area before going into the clean area. When the top sheet becomes too dirty, it may be pulled up, revealing another one underneath. Gloves not only restrict particles, skin oils, and salts from being spread by hands, but also protect hands from dangerous chemicals. Safety glasses protect eyes from chemical splashes, breakage, explosions, or other accidents. (Contact lenses are regarded as a hazard in environments that require safety glasses. Dangerous fluids can be trapped beneath lenses; they may be difficult to remove quickly, especially if this must be done by another person.) To restrict the use of cosmetics on exposed skin surfaces may be necessary for the highest cleanliness standards. Plastic shields are available to place in front of microscopes to prevent the breath of the viewer from contaminating the wafer on the microscope stage. Some or all operations can be performed in laminar flow hoods. These can be substantially cleaner than the adjacent environment, assuming that gloves are used by operators.

Paper is another source of particles. Lint-free paper is available for clean room use. Lead pencils or erases within clean rooms could generate large amounts of particles, and should be prohibited. Backside processing operations such as lapping, sawing, or scribing tend to be innately "dirty." These are usually performed in locations separated from the main process area.

Maintaining cleanliness in the process environment requires constant monitoring. As noted above, commercial equipment exists to measure the particle density in the air. This equipment can be used with numerous sensing tubes placed throughout the clean area, allowing many measurements per hour at various locations. Sudden elevations of particle count can thus be detected before harm occurs.

Another practice necessary in clean rooms is to use monitor wafers at periodic intervals to determine the amount of particles that a given process or piece of equipment is adding to the wafer. These procedures use commercially available equipment to measure the size and number of particles on a wafer by using laser scanning techniques. The equipment is sensitive to particle or defect sizes down to about 0.1 μm. Summary data (histograms) and defect maps are commonly available from such equipment. The procedure is to measure a pilot wafer before and after being run through the process or equipment being monitored. The number of added particles

indicates the cleanliness of the process. The frequency of monitoring can be from once per day to once per week, depending on the particular process and the number of wafers being processed. Occasionally, one may find a significant increase in particle contamination from a specific piece of equipment or process, allowing the process engineer to stop the process, find the problem, and fix it. Such a particle check should be a routine part of the qualification procedure for new or repaired equipment.

In fact, when such monitoring procedures are first adopted, one might sometimes find that "cleaning" steps, which were intended to remove particles, actually contributed additional particles. This relates to the fact that chemicals, especially liquids, are almost impossible to obtain particle-free, and can easily accumulate further particles from the environment. Liquid processes nearly always require point-of-use filters, or filters in a recirculating system to keep the particle count low. Point-of-use filters are also commonly used in gas systems.

4.2.2 Temperature and Humidity

Temperature and humidity need to be controlled within the clean room, principally for resist work. If *relative humidity* (RH) is too low (below about 20% RH), static also becomes a problem (see below). Extreme dryness can harm photoresist, which needs a certain amount of moisture, but there is greater danger to resist operations from high humidity (over about 50% RH). This applies to application, exposure, and developing. The resist can exhibit adhesion problems or cracking. Poor control of humidity in resist areas could cause enormous problems and it should be controlled to within 5% RH. Because of its importance, relative humidity should be continuously monitored. Atmospheric humidity loads are usually described in terms of the pounds of water vapor generated per hour. The units are grains (gr) of water vapor, where one grain is 1/7000 lb. Table 4.2 indicates typical moisture loads. In addition to the sources indicated in the table, moisture can enter through walls, cracks, and

Table 4.2
Typical Moisture Contributions of Various Sources
(from [5]; one grain (gr) is 1/7000 lb)

Source	Water Vapor Added (gr/r)
One person doing light work	1500 to 3500
Door opening	1000 to 3000
Exposed wet surfaces	140 to 700 (per ft^2 area)
Outside air (1000 CFM)	130,000 to 350,000 (depending on climate)

ductwork if these are not properly sealed. Airlocks are generally used at entrances to reduce moisture diffusion from outside air when doors are opened, as well as to reduce the entrance of particles stirred up in the area adjacent to the door. Nevertheless, air flow should be outward to ensure that moisture and particles would tend to leave the clean room rather than enter it.

Humidity control usually requires removal of moisture from the air; to add moisture is relatively easy if needed. There are two general methods used to lower relative humidity. The first is the use of desiccants. These are quite effective and cost efficient if the initial humidity level is low. Higher humidity levels require dehumidificaton by condensation. In this case, the incoming air is cooled to remove the moisture by condensation and then heated if necessary. Some systems use combinations of both approaches [5]. In typical operating conditions, most of the water vapor load is from incoming air. Hence, the system must be able to accommodate wide ranges of moisture content of incoming air. Although most of the moisutre load is from external (make-up) air, some is generated within the clean room (Table 4.3), and the air must be dry enough to act as a "sponge" and absorb this internal load. A rough calculation can indicate if this is possible. Let L be the internal moisture load (in gr/hr). Table 4.3 can be used to approximate L by using the number of people, number of door openings, exposed wet surface area, *et cetera*. Let W_r and W_a be the water content of the room and incoming air, respectively (each expressed in gr/lb). W_r can be determined from Table 4.3, knowing the temperature and relative humidity of the room air. W_a can be determined if the incoming air is dehumidified by the condensation technique: knowing the temperature to which the air was

Table 4.3
Relative Humidity and Water Content of Air
(from [6])

Relative Humidity (%)	Specific Humidity (gr/lb of air), for T in °F					
	40	*50*	*60*	*70*	*80*	*90*
10	4	5	8	10.5	15	20
20	7	10	15	22	30	42
30	10.5	16	23	33	46	63
40	14	21	30	44	60	84
50	17.5	26	38	55	76	105
60	21	31.5	46	65	92	125
70	25	37	54	76	107	149
80	28.5	42.5	61	87	123	171
90	32	48	69	99	140	193
100 (dew point)	36	53	77	110	156	217

cooled gives the water content (the dew point; see Table 4.3). If the incoming air flow rate is given in SCFM and the density of air is approximately 0.075 lb/ft^3, the maximum load, L_m, that the incoming air can accommodate is given by

$$L_m = \text{SCFM} \times 60 \text{ min/hr} \times 0.075 \text{ lb/ft}^3 \times (W_r - W_a)$$

$$= 4.5 \text{ SCFM } (W_r - W_a) \text{ gr/hr} \qquad (4.1)$$

If $L_m > L$, the incoming air can handle the moisture load generated in the room. Note that the condensation method limits the minimum value of W_a that can be obtained. That is, air is generally cooled to no less than about 40° F to prevent frost problems. At this temperature, $W_a = 36$ gr/lb. If this value, as used in (4.1), results in $L_m < L$, the humidity in the room will rise. The amount of change can be determined by solving

$$L = 4.5 \text{ SCFM } (W_r - W_a)$$

for W_r, and then using Table 4.3 to determine the relative humidity to which that value corresponds. If the condensation method is insufficient to accommodate the internal moisture load, the system must be augmented by a desiccant method. The amount of difficulty in using condensation alone will depend on the amount of room air that is exhausted and replaced by make-up air. The exhaust air may contain dangerous fumes, and thus cannot be recycled.

4.2.3 Static Electricity

Static in GaAs fabrication is not as severe a problem as it is for many silicon devices, which often employ thin oxides (MOS devices) that can easily be damaged by minor static charge. Although completed GaAs devices can be damaged by static charge, especially during bonding operations where there is a path through a Schottky gate to an ohmic contact, GaAs devices seem rather insensitive to static damage during fabrication. Unfortunately, this does not mean that static can be ignored. Static charge attracts and binds particles to wafers or other surfaces. The electrostatic force between the surface and the particle can be substantial, making removal extremely difficult. Static can be reduced by several means, not the least of which is good humidity control (especially in winter). Conductive floor material or waxes are available to alleviate charge buildup on personnel. Deionizing nuclear cartridges can be used on air guns, where rapid air flow tends to generate static charge. Even possible is to install ion "spray" grids for the entire room, although these are not a standard item in most clean rooms. Many items intended for use within clean rooms can be obtained constructed of "static-free" (i.e., somewhat conductive) materials. These

include wafer containers, storage cabinets, and even antistatic clothing and booties. Commercial instruments exist to measure static charge, and routine monitoring is advisable.

4.2.4 Wafer Handling

GaAs wafers are notoriously susceptible to breakage. Dropping a wafer only a few inches can shatter it. Even if the wafer remains whole, strains may be introduced that result in breakage at a subsequent step. Minor scratches can initiate cleaves. Avoid handling by tweezers as much as possible; vacuum tweezers work well. Most importantly, wafers should never be touched by ungloved hands. Oils and salts from human skin are easily transferred to objects by the slightest touch, and are then very difficult to remove. In fact, a severe test of any cleaning process is attempting to remove a fingerprint. This type of contamination can be insidious because the contaminant may transfer from object to object. Therefore, personnel must not touch any object that itself will touch a wafer. Obviously, this caution can be carried to ridiculous extremes, but is intended to apply to such actions as touching the ends of vacuum tweezers with a bare finger to see if the vacuum is on.

In-process storage of wafers is usually in closed cabinets that are continuously purged with dry nitrogen to keep oxygen, atmospheric vapors, and moisture away from the wafers. This seems especially helpful if the wafers have a resist film spun on them, or are being stored for extended durations, such as overnight or over weekends. Normally, resist films are not left on wafers for any extended time before exposure and development.

4.3 CLEANING TECHNIQUES

Cleaning operations are performed before all major steps during device processing. These steps may employ organic solvents, vapor degreasing, acids, bases, or plasma etches. Chemical purity is obviously important, and many of the commonly used solvents, acids, and bases may be obtained in *semiconductor grade* (SC grade), which is one step above *reagent grade*. The major improvement in purity is the reduction of metal contaminants. There are also a number of commercially available proprietary compositions useful for cleaning, resist stripping, or oxide removal. Although they may largely be mixtures of common solvents or acids, these compositions may also include buffering agents or other constituents that aid in the chemical action. As a general rule, such compositions are worth using.

4.3.1 Solvent Cleaning

Organic solvents are effective in removing oils, greases, waxes, and organic material such as photoresist. Organic solvents are also innocuous to almost all materials intended to be permanently present on GaAs devices. Such materials include GaAs, metals, and dielectrics. Some properties of solvents used in GaAs processing are listed in Table 4.4. Solvent cleaning is usually done at elevated temperatures, even

Table 4.4
Solvents and Properties
(Most data from [7])

Solvents	Boiling Point (°C)	Flash Point (°C)[a]	Water Sol.	Density (g/ml)[b]	Safety[c]
Acetone	56.2	−16	100%	.784	F
Benzene	80.1	−11	<1%	.874	F[C,N]
n-Butyl acetate	126	22	<1%	.876	F
Carbon tetrachloride (tetrachloroethylene)	76.8	none	<1%	1.58	[C,N,T]
Chlorobenzene	132	29	<1%	1.10	F
ortho-dichlorobenzene	180	74	<1%	1.3	
Ethanol	78.5	60	100%		
Ethylene dichloride	83.5	13	<1%	1.25	F [C]
Isobutyl alcohol	108	35	8.5%	.798	F [C]
Methanol	64.7	12	100%	.787	F
Methyl ethyl keytone	79.6	−1	24%	.800	F [T]
Methylene chloride	39.8	none	1.6%	1.32	
Propanol-1	97.2	25	100%	.800	F [C]
Propanol-2 (isopropyl alcohol)	82.3	22	100%	.781	F
Tetrachloroethylene (perchloroethyane)	121	none	<1%	1.62	
Trichloroethylene	87.2	none	<1%	1.45	

NOTES:
[a] Flash point temperatures depend on the conditions of measurement; different references may give slightly different values.
[b] At 25° C.
[c] F = Flammable;
[C] = Possible carcinogen;
[N] = Possible neoplastic agent (cause nonmalignant tumor);
[T] = Possible Teratogen (cause physical defects in developing embryo).

at the boiling point of the solvent. Cleaning may also occur in a vapor degreaser using solvent vapors. This is a particularly clean method in that the solvent is constantly being distilled; only vapors condense on the slice. However, this seemingly clean procedure still must be used with caution. Contaminants on wafer holders may be moved onto wafers. In fact, vapor degreasing is not used often in semiconductor processing. The more common practice is to immerse the wafer in the heated solvent, or to spray the solvent onto the wafer while it is spinning (commercial equipment exists for this purpose, but safety considerations are important when solvents are under pressure). Agitation during immersion steps can also aid in removal of inorganic (or "stubborn" organic) particles. However, solvent cleaning can also remove organics from around inorganic particles, leaving them dry and more firmly adherent to the surface than before.

The debris removed during solvent cleaning accumulates in the solvent. Except in the case of vapor degreasing, these contaminants can be deposited on subsequent wafers. Therefore, solvents must be discarded and replaced at regular intervals, or continuously filtered to prevent accumulation of debris. Solvents may be toxic, flammable, and explosive. There is also evidence that some may be carcinogens, *neoplastic agents*, or *teratogens* (a neoplastic agent is a substance that causes nonmalignant tumors; a teratogen is a substance that causes physical defects in a developing embryo). The evidence for such claims is based on animal studies using large quantities of the substance, and the validity of such studies continues to be debated. Nevertheless, it is clearly wise to be prudent. Table 4.4 shows some substances suspected of having these dangers. Because solvents tend to be used when hot, or even boiling, good ventilation and safety practices ought to be observed to prevent personnel from being exposed to solvent vapors. Use of solvents in well exhausted fume hoods is recommended. Disposal of used solvents usually requires special arrangements to prevent contaminating the environment.

There are several proprietary compositions popular in semiconductor processing. One is a composition called J-100 (a trademark of Indust-Ri-Chem Laboratory, Inc.), used as a resist stripper in the silicon industry. J-100 is a combination of solvents and phenol (carbolic acid), and is a very powerful cleaner. If applied in full strength, it will slowly attack many metals, such as AuGe-Ni ohmic contacts, and so must be used cautiously after metal patterns are present on the wafer. J-100 can be used to remove stubborn material (usually resist remnants), and is very effective in the initial cleanup of wafers before any metal is present on them.

Waxes are sometimes used in GaAs processing to mount wafers on stronger substrates (e.g., for lapping or handling after lapping). Waxes are somewhat soluble in solvents, usually more so in one kind than another. For example, polyglycol is soluble in acetone, parafin is soluble in tetracholoroethylene (perchloroethylene).

After solvents are used, they must in turn be removed from the wafer. Some are more difficult to remove than others. As we see in Table 4.4, many are not soluble in water. Most solvents, however, are soluble to some extent in alcohols,

which are completely miscible with water. This property is one reason that solvent cleaning operations may use a sequence of solvents, the last one usually being an alcohol. A solvent such as xylene or perchloroetylene is useful to remove J-100. As with many other processes, the exact cleaning schedules (solvent types, order, times, and temperatures) of device manufactures are often considered proprietary. However, there is very little that is special or subtle. A minor amount of experimentation should yield quite adequate solvent cleaning procedures. As noted above, most solvents are relatively innocuous to the materials used in GaAs device fabrication. Solvents are also good cleaners. Therefore, solvent cleanup forms a major part of a process flow, occurring at almost every step for which cleaning is needed, including prior to application of resist or dielectric films.

4.3.2 Acids and Bases

Acids are used in cleaning steps to remove metal contaminants, to remove oxides, as part of wet etchants to remove GaAs material, and to provide a fresh surface. The latter two uses are the principal ones. GaAs etchants (Chapter 5) generally employ an acid as one component; these etchants may be used in cleaning to remove a small amount of surface material and expose fresh, "clean" GaAs. Such etchants usually employ oxidizing agents, and hence leave an oxide layer on the etched surface. Also, ashering in oxygen plasmas (see below, and Chapter 9) oxidizes the surface. Ordinary exposure to air will result in oxide on GaAs surfaces. This oxide, depending on previous steps, is generally between 10 Å and 50 Å thick. An acid can remove this oxide, and the acid alone usually will not etch the GaAs. To remove such oxides may be helpful before metalizations or application of dielectrics, although some special cases may benefit from the presence of an oxide. Acids used for oxide removal or cleaning are usually applied in highly diluted concentrations (using deionized (DI) water). The choice of acid depends on the materials present on the slice. Diluted HCl is a common choice. Another compound that is excellent for removing oxides is the commercially available compound Bell #2, which consists mainly of buffered hydrofluoric acid (HF).

The danger of acids to personnel is well known, but to emphasize the dangers associated with HF is useful. This acid is especially dangerous because it can be absorbed through the skin with little or no pain, and then cause serious tissue and bone damage before pain begins.

Bases or alkaline solutions can act as cleaners for some types of soils. Also, because oxides formed on GaAs tend to be amphoteric, bases as well as acids can be used to dissolve the oxide. Again, these are usually used in diluted concentrations. Bases tend to cause photoresist adhesion problems, and caution should be observed when considering their use in the presence of resist patterns.

4.3.3 Plasma Etching

Plasma etching can be used for cleaning; these techniques are described in Chapter 9. Oxygen plasmas are used to remove organics from the slice (ashering). The plasma causes O_2 to dissociate into highly reactive oxygen molecules that react with carbon and hydrogen in organics to produce volatile waste products (CO, CO_2, H_2O). Ashering may be used to remove resist, as a "descum" to remove thin films of resist in developed areas, or as a general technique to remove organics. Sometimes, ashering is more successful than liquid solvents in removing stubborn material. Oxygen plasmas will not etch exposed GaAs surfaces, but the process will leave an oxide on such surfaces. These oxides may require removal before subsequent process steps.

4.3.4 Other Issues

Small particles can be very difficult to remove from a wafer. Electrostatic forces can bind such low-mass particles to the surface with extraordinary force. Further, forceful blowing of gases may not be effective because the particles may be small enough to be inside the nearly stagnant boundary layer present at the wafer surface under laminar flow. Mechanical means may be necessary to remove these particles. On a small scale, they may be removed by swabbing. On a larger scale, commercial machines exist to perform such operations. These machines may also be used to clean photomasks.

Water is part of many processing operations, including rinsing. In semiconductor processing, DI water is used. The quality of the water is assessed by its resistivity. DI water should be over 10 MΩ. Stagnant water will tend to decrease in resistivity, and we may need to have the water flow for some time after it is first turned on each morning. The water should also be filtered in the submicron regime to remove particles. The general DI water system should consist of continuous loops as dead ends can support bacterial growth. There are commercial companies that specialize in engineering DI water systems.

Drying is an important consideration after rinsing wafers. If drying occurs in a haphazard manner, solvent or water stains will remain on the wafer. An example is shown in Figure 4.1. These stains may result from trace contaminants in the solutions. Drying proceeds best if the film of liquid (i.e., water, alcohol) is removed in one continuous sheet, rather than being broken into individual drops before drying. Such drops are good sources of residue that will be carried off the wafer if the liquid is removed in one sheet. Compressed air is generally not a good choice for wafer drying because it tends to contain moisture and, worse still, trace amounts of oil from the compressor. Dry nitrogen is commonly used because it is pure and economical. It can be derived as a by-product of liquid nitrogen evaporation. Liquid nitrogen is often available in processing facilities due to its use in cold traps. Filters
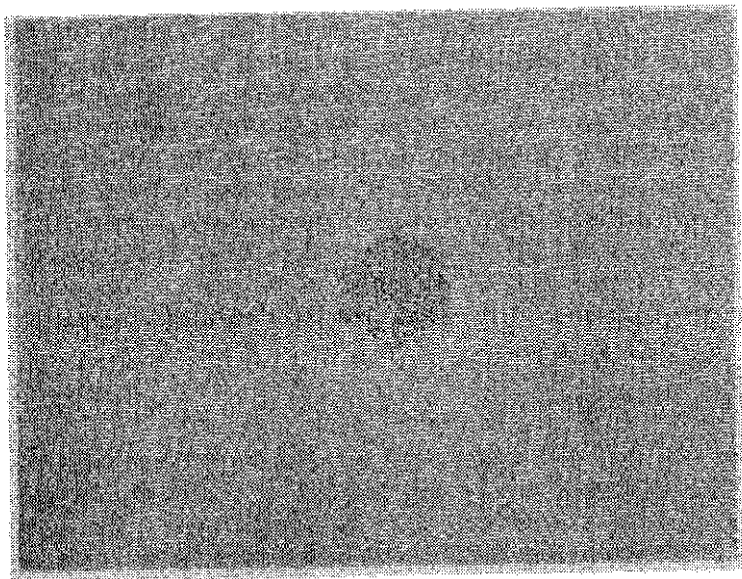
Figure 4.1 Solvent stains on GaAs wafer.

or nuclear deionizing cartridges are used in "air" guns to remove particles and to alleviate static.

A common method used to dry wafers is to spin them at high speed, which dispels the liquid. Commercial equipment exists to handle wafer boats that sprays a sequence of liquids on the wafers and then spins the entire boat of wafers.

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